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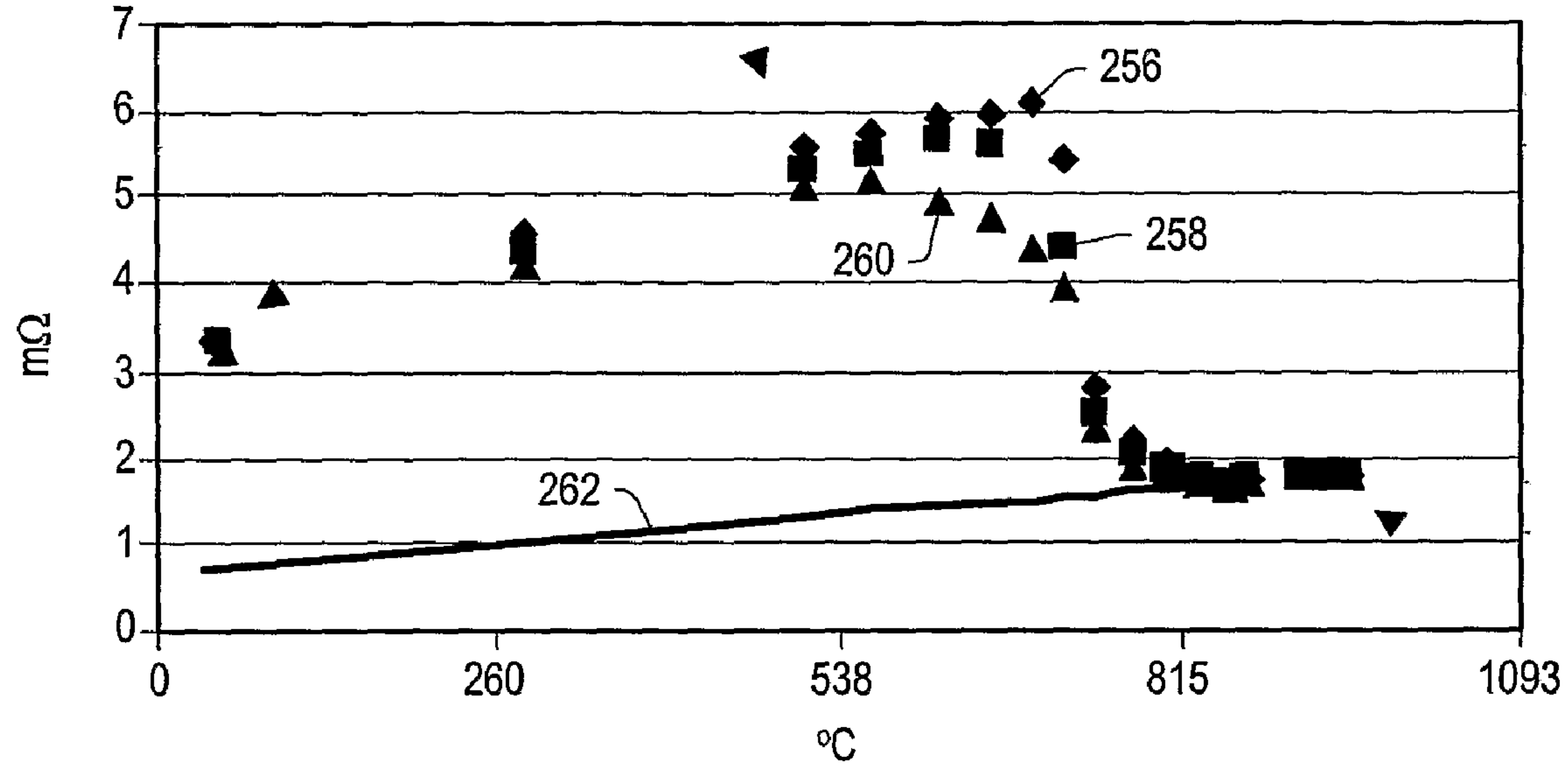

(57) Abrégé/Abstract:
A heater is described. The heater includes a ferromagnetic conductor (242) and an electrical conductor (244) electrically coupled to the ferromagnetic conductor. The ferromagnetic conductor is positioned relative to the electrical conductor such that an electromagnetic field produced by- time-varying current flow in the ferromagnetic conductor confines a majority of the flow of the electrical current to the electrical conductor at temperatures below or near a selected temperature .

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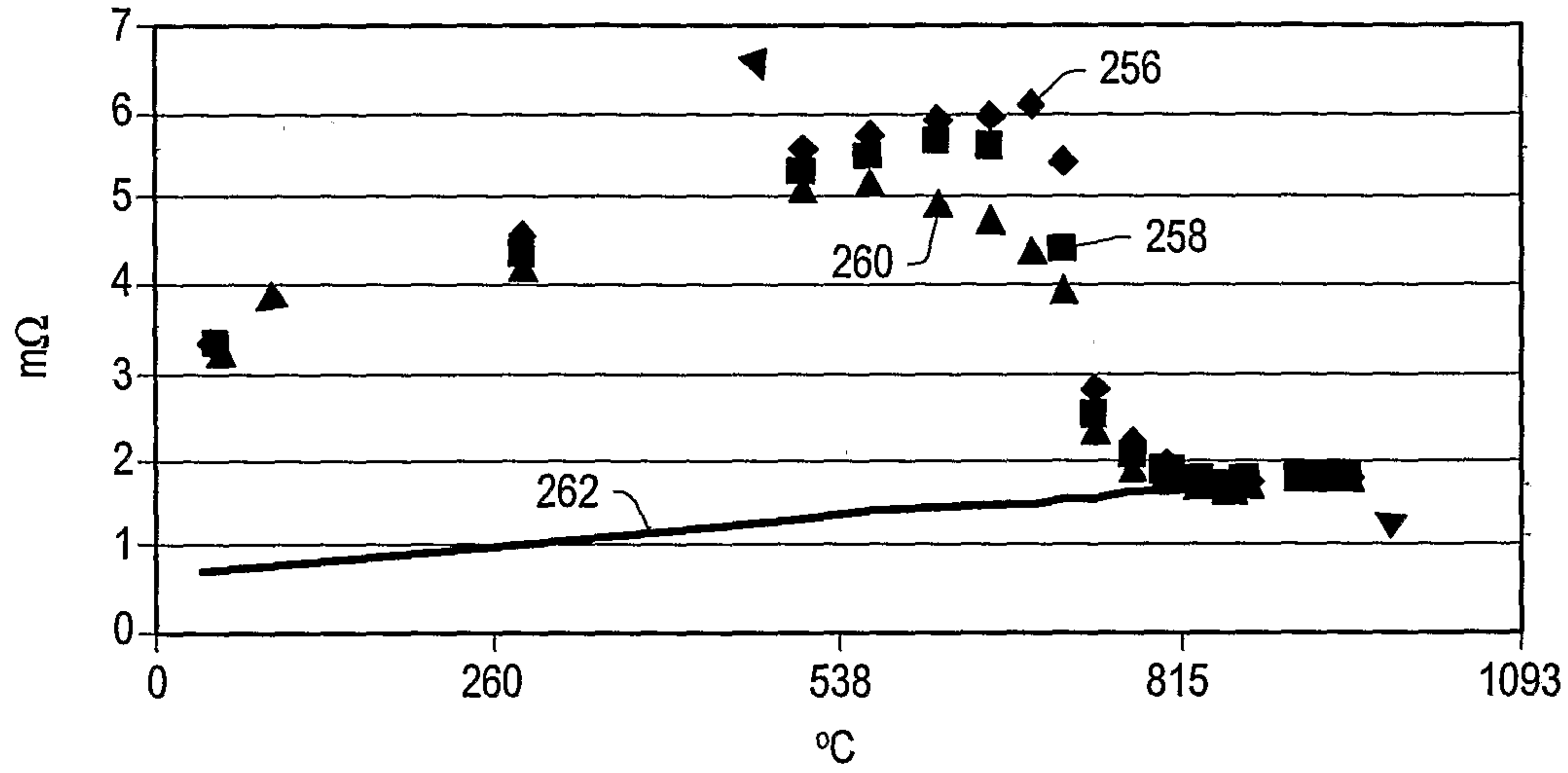

(57) **Abstract:** A heater is described. The heater includes a ferromagnetic conductor (242) and an electrical conductor (244) electrically coupled to the ferromagnetic conductor. The ferromagnetic conductor is positioned relative to the electrical conductor such that an electromagnetic field produced by- time-varying current flow in the ferromagnetic conductor confines a majority of the flow of the electrical current to the electrical conductor at temperatures below or near a selected temperature .

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TEMPERATURE LIMITED HEATER UTILIZING NON-FERROMAGNETIC CONDUCTOR

BACKGROUND

1. Field of the Invention

The present invention relates generally to methods and systems for heating and production of hydrocarbons, hydrogen, and/or other products from various subsurface formations such as hydrocarbon containing formations. Embodiments relate to temperature limited heaters used to heat subsurface formations.

2. Description of Related Art

Hydrocarbons obtained from subterranean formations are often used as energy resources, as feedstocks, and as consumer products. Concerns over depletion of available hydrocarbon resources and concerns over declining overall quality of produced hydrocarbons have led to development of processes for more efficient recovery, processing and/or use of available hydrocarbon resources. In situ processes may be used to remove hydrocarbon materials from subterranean formations. Chemical and/or physical properties of hydrocarbon material in a subterranean formation may need to be changed to allow hydrocarbon material to be more easily removed from the subterranean formation. The chemical and physical changes may include in situ reactions that produce removable fluids, composition changes, solubility changes, density changes, phase changes, and/or viscosity changes of the hydrocarbon material in the formation. A fluid may be, but is not limited to, a gas, a liquid, an emulsion, a slurry, and/or a stream of solid particles that has flow characteristics similar to liquid flow.

Heaters may be placed in wellbores to heat a formation during an in situ process. Examples of in situ processes utilizing downhole heaters are illustrated in U.S. Patent Nos. 2,634,961 to Ljungstrom; 2,732,195 to Ljungstrom; 2,780,450 to Ljungstrom; 2,789,805 to Ljungstrom; 2,923,535 to Ljungstrom; and 4,886,118 to Van Meurs et al.

Application of heat to oil shale formations is described in U.S. Patent Nos. 2,923,535 to Ljungstrom and 4,886,118 to Van Meurs et al. Heat may be applied to the oil shale formation to pyrolyze kerogen in the oil shale formation. The heat may also fracture the formation to increase permeability of the formation. The increased permeability may allow formation fluid to travel to a production well where the fluid is removed from the oil shale formation. In some processes disclosed by Ljungstrom, for example, an oxygen containing gaseous medium is introduced to a permeable stratum, preferably while still hot from a preheating step, to initiate combustion.

A heat source may be used to heat a subterranean formation. Electric heaters may be used to heat the subterranean formation by radiation and/or conduction. An electric heater may resistively heat an element. U.S. Patent No. 2,548,360 to Germain describes an electric heating element placed in a viscous oil in a wellbore. The heater element heats and thins the oil to allow the oil to be pumped from the wellbore. U.S. Patent No. 4,716,960 to Eastlund et al. describes electrically heating tubing of a petroleum well by passing a relatively low voltage current through the tubing to prevent formation of solids. U.S. Patent No. 5,065,818 to Van Egmond describes an electric heating element that is cemented into a well borehole without a casing surrounding the heating element.

Some heaters may break down or fail due to hot spots in the formation. The power supplied to the entire heater may need to be reduced if a temperature along any point of the heater exceeds, or is about to exceed, a maximum operating temperature of the heater to avoid failure of the heater and/or overheating of the formation at or near hot spots in the formation. Some heaters may not provide uniform heat along a length of the heater until the heater reaches a certain temperature limit. Some heaters may not heat a subsurface formation efficiently. Thus, it is advantageous to have a heater that provides uniform heat along a length of the heater; heats the subsurface formation efficiently; provides automatic temperature adjustment when a portion of the heater approaches a selected temperature; and/or has substantially linear magnetic properties and a high power factor below the selected temperature.

SUMMARY

Embodiments described herein generally relate to systems, methods, and heaters for treating a subsurface formation. Embodiments described herein also generally relate to heaters that have novel components therein. Such heaters can be obtained by using the systems and methods described herein.

In certain embodiments, the invention provides one or more systems, methods, and/or heaters. In some embodiments, the systems, methods, and/or heaters are used for treating a subsurface formation.

In certain embodiments, the invention provides a heater, comprising: a ferromagnetic conductor; and an electrical conductor electrically coupled to the ferromagnetic conductor, wherein the ferromagnetic conductor is positioned relative to the electrical conductor such that an electromagnetic field produced by time-varying current flow in the ferromagnetic conductor confines a majority of the flow of the electrical current to the electrical conductor at temperatures below or near a selected temperature.

In further embodiments, features from specific embodiments may be combined with features from other embodiments. For example, features from one embodiment may be combined with features from any of the other embodiments.

In further embodiments, treating a subsurface formation is performed using any of the methods, systems, or heaters described herein.

In further embodiments, additional features may be added to the specific embodiments described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

Advantages of the present invention may become apparent to those skilled in the art with the benefit of the following detailed description and upon reference to the accompanying drawings in which:

FIG. 1 depicts an illustration of stages of heating a hydrocarbon containing formation.

FIG. 2 shows a schematic view of an embodiment of a portion of an in situ conversion system for treating a hydrocarbon containing formation.

FIG. 3 depicts a cross-sectional representation of an embodiment of a conductor-in-conduit heat source.

FIG. 4 depicts a cross-sectional representation of an embodiment of a removable conductor-in-conduit heat source.

FIG. 5 depicts an embodiment of a temperature limited heater in which the support member provides a majority of the heat output below the Curie temperature of the ferromagnetic conductor.

FIGS. 6 and 7 depict embodiments of temperature limited heaters in which the jacket provides a majority of the heat output below the Curie temperature of the ferromagnetic conductor.

FIGS. 8A and 8B depict cross-sectional representations of an embodiment of the temperature limited heater with triaxial conductors.

FIG. 9 depicts a high temperature embodiment of a temperature limited heater.

FIG. 10 depicts experimentally measured resistance versus temperature at several currents for a temperature limited heater with a copper core, a carbon steel ferromagnetic conductor, and a stainless steel 347H stainless steel support member.

FIG. 11 depicts experimentally measured resistance versus temperature at several currents for a temperature limited heater with a copper core, an iron-cobalt ferromagnetic conductor, and a stainless steel 347H stainless steel support member.

FIG. 12 depicts experimentally measured power factor versus temperature at two AC currents for a temperature limited heater with a copper core, a carbon steel ferromagnetic conductor, and a 347H stainless steel support member.

FIG. 13 depicts experimentally measured turndown ratio versus maximum power delivered for a temperature limited heater with a copper core, a carbon steel ferromagnetic conductor, and a 347H stainless steel support member.

FIG. 14 depicts examples of relative magnetic permeability versus magnetic field for both the found correlations and raw data for carbon steel.

FIG. 15 shows the resulting plots of skin depth versus magnetic field for four temperatures and 400 A current.

FIG. 16 shows a comparison between the experimental and numerical (calculated) results for currents of 300 A, 400 A, and 500 A.

FIG. 17 shows the AC resistance per foot of the heater element as a function of skin depth at 1100 °F calculated from the theoretical model.

FIG. 18 depicts the power generated per unit length in each heater component versus skin depth for a temperature limited heater.

FIGS. 19A-C compare the results of theoretical calculations with experimental data for resistance versus temperature in a temperature limited heater.

While the invention is susceptible to various modifications and alternative forms, specific embodiments thereof are shown by way of example in the drawings and may herein be described in detail. The drawings may not be to scale. It should be understood, however, that the drawings and detailed description thereto are not intended to limit the invention to the particular form disclosed, but on the contrary, the intention is to cover all modifications, equivalents and alternatives falling within the spirit and scope of the present invention as defined by the appended claims.

DETAILED DESCRIPTION

The following description generally relates to systems and methods for treating hydrocarbons in the formations. Such formations may be treated to yield hydrocarbon products, hydrogen, and other products.

"Hydrocarbons" are generally defined as molecules formed primarily by carbon and hydrogen atoms. Hydrocarbons may also include other elements such as, but not limited to, halogens, metallic elements, nitrogen, oxygen, and/or sulfur. Hydrocarbons may be, but are not limited to, kerogen, bitumen, pyrobitumen, oils, natural mineral waxes, and asphaltites. Hydrocarbons may be located in or adjacent to mineral matrices in the earth. Matrices may include, but are not limited to, sedimentary rock, sands, silicilytes, carbonates, diatomites, and other porous media. "Hydrocarbon fluids" are fluids that include hydrocarbons. Hydrocarbon fluids may include, entrain, or be entrained in non-hydrocarbon fluids such as hydrogen, nitrogen, carbon monoxide, carbon dioxide, hydrogen sulfide, water, and ammonia.

A "formation" includes one or more hydrocarbon containing layers, one or more non-hydrocarbon layers, an overburden, and/or an underburden. The "overburden" and/or the "underburden" include one or more different types of impermeable materials. For example, overburden and/or underburden may include rock, shale, mudstone, or wet/tight carbonate. In some embodiments of in situ conversion processes, the overburden and/or the underburden may include a hydrocarbon containing layer or hydrocarbon containing layers that are relatively impermeable and are not subjected to temperatures during in situ conversion processing that result in significant characteristic changes of the hydrocarbon containing layers of the overburden and/or the underburden. For example, the underburden may contain shale or mudstone, but the underburden is not allowed to heat to pyrolysis temperatures during the in situ conversion process. In some cases, the overburden and/or the underburden may be somewhat permeable.

A "heat source" is any system for providing heat to at least a portion of a formation substantially by conductive and/or radiative heat transfer. For example, a heat source may include electric heaters such as an insulated conductor, an elongated member, and/or a conductor disposed in a conduit. A heat source may also include systems that generate heat by burning a fuel external to or in a formation. The systems may be surface burners, downhole gas burners, flameless distributed combustors, and natural distributed combustors. In some embodiments, heat provided to or generated in one or more heat sources may be supplied by other sources of energy. The other sources of energy may directly heat a formation, or the energy may be applied to a transfer medium that directly or indirectly heats the formation. It is to be understood that one or more heat sources that are applying heat to a formation may use different sources of energy. Thus, for example, for a given formation some heat sources may supply heat from electric resistance heaters, some heat sources may provide heat from combustion, and some heat sources may provide heat from one or more other energy sources (for example, chemical reactions, solar energy, wind energy, biomass, or other sources of renewable energy). A chemical reaction may include an exothermic reaction (for example, an oxidation reaction). A heat source may also include a heater that provides heat to a zone proximate and/or surrounding a heating location such as a heater well.

A "heater" is any system or heat source for generating heat in a well or a near wellbore region. Heaters may be, but are not limited to, electric heaters, burners, combustors that react with material in or produced from a formation, and/or combinations thereof.

An "in situ conversion process" refers to a process of heating a hydrocarbon containing formation from heat sources to raise the temperature of at least a portion of the formation above a pyrolysis temperature so that pyrolyzation fluid is produced in the formation.

"Insulated conductor" refers to any elongated material that is able to conduct electricity and that is covered, in whole or in part, by an electrically insulating material.

An elongated member may be a bare metal heater or an exposed metal heater. "Bare metal" and "exposed metal" refer to metals that do not include a layer of electrical insulation, such as mineral insulation, that is designed to provide electrical insulation for the metal throughout an operating temperature range of the elongated member. Bare metal and exposed metal may encompass a metal that includes a corrosion inhibiter such as a naturally occurring oxidation layer, an applied oxidation layer, and/or a film. Bare metal and exposed metal include metals with polymeric or other types of electrical insulation that cannot retain electrical insulating properties at typical operating temperature of the elongated member. Such material may be placed on the metal and may be thermally degraded during use of the heater.

"Temperature limited heater" generally refers to a heater that regulates heat output (for example, reduces heat output) above a specified temperature without the use of external controls such as temperature controllers, power regulators, rectifiers, or other devices. Temperature limited heaters may be AC (alternating current) or modulated (for example, "chopped") DC (direct current) powered electrical resistance heaters.

"Curie temperature" is the temperature above which a ferromagnetic material loses all of its ferromagnetic properties. In addition to losing all of its ferromagnetic properties above the Curie temperature, the ferromagnetic material begins to lose its ferromagnetic properties when an increasing electrical current is passed through the ferromagnetic material.

"Time-varying current" refers to electrical current that produces skin effect electricity flow in a ferromagnetic conductor and has a magnitude that varies with time. Time-varying current includes both alternating current (AC) and modulated direct current (DC).

"Alternating current (AC)" refers to a time-varying current that reverses direction substantially sinusoidally. AC produces skin effect electricity flow in a ferromagnetic conductor.

"Modulated direct current (DC)" refers to any substantially non-sinusoidal time-varying current that produces skin effect electricity flow in a ferromagnetic conductor.

"Turndown ratio" for the temperature limited heater is the ratio of the highest AC or modulated DC resistance below the Curie temperature to the lowest resistance above the Curie temperature for a given current.

In the context of reduced heat output heating systems, apparatus, and methods, the term "automatically" means such systems, apparatus, and methods function in a certain way without the use of external control (for example, external controllers such as a controller with a temperature sensor and a feedback loop, PID controller, or predictive controller).

The term "wellbore" refers to a hole in a formation made by drilling or insertion of a conduit into the formation. A wellbore may have a substantially circular cross section, or another cross-sectional shape. As used herein, the terms "well" and "opening," when referring to an opening in the formation may be used interchangeably with the term "wellbore."

Hydrocarbons in formations may be treated in various ways to produce many different products. In certain embodiments, hydrocarbons in formations are treated in stages. FIG. 1 depicts an illustration of stages of heating the hydrocarbon containing formation. FIG. 1 also depicts an example of yield ("Y") in barrels of oil equivalent per ton (y axis) of formation fluids from the formation versus temperature ("T") of the heated formation in degrees Celsius (x axis).

Desorption of methane and vaporization of water occurs during stage 1 heating. Heating of the formation through stage 1 may be performed as quickly as possible. For example, when the hydrocarbon containing formation is initially heated, hydrocarbons in the formation desorb adsorbed methane. The desorbed methane may be produced from the formation. If the hydrocarbon containing formation is heated further, water in the hydrocarbon containing formation is vaporized. Water may occupy, in some hydrocarbon containing formations, between 10% and 50% of the pore volume in the formation. In other formations, water occupies larger or smaller portions of the pore volume. Water typically is vaporized in a formation between 160 °C and 285 °C at pressures of 600 kPa absolute to 7000 kPa absolute. In some embodiments, the vaporized water produces wettability changes in the formation and/or increased formation pressure. The wettability changes and/or increased pressure may affect pyrolysis reactions or other reactions in the formation. In certain embodiments, the vaporized water is produced from the formation. In other embodiments, the vaporized water is used for steam extraction and/or distillation in the formation or outside the formation. Removing the water from and increasing the pore volume in the formation increases the storage space for hydrocarbons in the pore volume.

In certain embodiments, after stage 1 heating, the formation is heated further, such that a temperature in the formation reaches (at least) an initial pyrolyzation temperature (such as a temperature at the lower end of the temperature range shown as stage 2). Hydrocarbons in the formation may be pyrolyzed throughout stage 2. A pyrolysis temperature range varies depending on the types of hydrocarbons in the formation. The pyrolysis temperature range may include temperatures between 250 °C and 900 °C. The pyrolysis temperature range for producing desired products may extend through only a portion of the total pyrolysis temperature range. In some embodiments, the pyrolysis temperature range for producing desired products may include temperatures between 250 °C and 400 °C or temperatures between 270 °C and 350 °C. If a temperature of hydrocarbons in the formation is slowly raised through the temperature range from 250 °C to 400 °C, production of pyrolysis products may be substantially complete when the temperature approaches 400 °C. Average temperature of the hydrocarbons may be raised at a rate of less than 5 °C per day, less than 2 °C per day, less than 1 °C per day, or less than 0.5 °C per day through the pyrolysis temperature range for producing desired products. Heating the hydrocarbon containing formation with a plurality of heat sources may establish thermal gradients around the heat sources that slowly raise the temperature of hydrocarbons in the formation through the pyrolysis temperature range.

The rate of temperature increase through the pyrolysis temperature range for desired products may affect the quality and quantity of the formation fluids produced from the hydrocarbon containing formation. Raising the temperature slowly through the pyrolysis temperature range for desired products may inhibit mobilization of large chain molecules in the formation. Raising the temperature slowly through the pyrolysis temperature range for desired products may limit reactions between mobilized hydrocarbons that produce undesired products. Slowly raising the temperature of the formation through the pyrolysis temperature range for desired products may allow for the production of high quality, high API gravity hydrocarbons from the formation. Slowly raising the temperature of the formation through the pyrolysis temperature range for desired products may allow for the removal of a large amount of the hydrocarbons present in the formation as hydrocarbon product.

In some in situ conversion embodiments, a portion of the formation is heated to a desired temperature instead of slowly heating the temperature through a temperature range. In some embodiments, the desired temperature is 300 °C, 325 °C, or 350 °C. Other temperatures may be selected as the desired temperature. Superposition of heat from heat sources allows the desired temperature to be relatively quickly and efficiently established in the formation. Energy input into the formation from the heat sources may be adjusted to maintain the temperature in the formation substantially at the desired temperature. The heated portion of the formation is maintained substantially at the desired temperature until pyrolysis declines such that production of desired formation fluids from the formation becomes uneconomical. Parts of the formation that are subjected to pyrolysis may include regions brought into a pyrolysis temperature range by heat transfer from only one heat source.

In certain embodiments, formation fluids including pyrolyzation fluids are produced from the formation. As the temperature of the formation increases, the amount of condensable hydrocarbons in the produced formation fluid may decrease. At high temperatures, the formation may produce mostly methane and/or hydrogen. If the hydrocarbon containing formation is heated throughout an entire pyrolysis range, the formation may produce only small amounts of hydrogen towards an upper limit of the pyrolysis range. After all of the available hydrogen is depleted, a minimal amount of fluid production from the formation will typically occur.

After pyrolysis of hydrocarbons, a large amount of carbon and some hydrogen may still be present in the formation. A significant portion of carbon remaining in the formation can be produced from the formation in the form of synthesis gas. Synthesis gas generation may take place during stage 3 heating depicted in FIG. 1. Stage 3 may include heating a hydrocarbon containing formation to a temperature sufficient to allow synthesis gas generation. For example, synthesis gas may be produced in a temperature range from 400 °C to 1200 °C, 500 °C to

1100 °C, or 550 °C to 1000 °C. The temperature of the heated portion of the formation when the synthesis gas generating fluid is introduced to the formation determines the composition of synthesis gas produced in the formation. The generated synthesis gas may be removed from the formation through a production well or production wells.

Total energy content of fluids produced from the hydrocarbon containing formation may stay relatively constant throughout pyrolysis and synthesis gas generation. During pyrolysis at relatively low formation temperatures, a significant portion of the produced fluid may be condensable hydrocarbons that have a high energy content. At higher pyrolysis temperatures, however, less of the formation fluid may include condensable hydrocarbons. More non-condensable formation fluids may be produced from the formation. Energy content per unit volume of the produced fluid may decline slightly during generation of predominantly non-condensable formation fluids. During synthesis gas generation, energy content per unit volume of produced synthesis gas declines significantly compared to energy content of pyrolyzation fluid. The volume of the produced synthesis gas, however, will in many instances increase substantially, thereby compensating for the decreased energy content.

FIG. 2 depicts a schematic view of an embodiment of a portion of the in situ conversion system for treating the hydrocarbon containing formation. The in situ conversion system may include barrier wells 200. Barrier wells are used to form a barrier around a treatment area. The barrier inhibits fluid flow into and/or out of the treatment area. Barrier wells include, but are not limited to, dewatering wells, vacuum wells, capture wells, injection wells, grout wells, freeze wells, or combinations thereof. In some embodiments, barrier wells 200 are dewatering wells. Dewatering wells may remove liquid water and/or inhibit liquid water from entering a portion of the formation to be heated, or to the formation being heated. In the embodiment depicted in FIG. 2, the barrier wells 200 are shown extending only along one side of heat sources 202, but the barrier wells typically encircle all heat sources 202 used, or to be used, to heat a treatment area of the formation.

Heat sources 202 are placed in at least a portion of the formation. Heat sources 202 may include heaters such as insulated conductors, conductor-in-conduit heaters, surface burners, flameless distributed combustors, and/or natural distributed combustors. Heat sources 202 may also include other types of heaters. Heat sources 202 provide heat to at least a portion of the formation to heat hydrocarbons in the formation. Energy may be supplied to heat sources 202 through supply lines 204. Supply lines 204 may be structurally different depending on the type of heat source or heat sources used to heat the formation. Supply lines 204 for heat sources may transmit electricity for electric heaters, may transport fuel for combustors, or may transport heat exchange fluid that is circulated in the formation.

Production wells 206 are used to remove formation fluid from the formation. In some embodiments, production well 206 may include one or more heat sources. A heat source in the production well may heat one or more portions of the formation at or near the production well. A heat source in a production well may inhibit condensation and reflux of formation fluid being removed from the formation.

Formation fluid produced from production wells 206 may be transported through collection piping 208 to treatment facilities 210. Formation fluids may also be produced from heat sources 202. For example, fluid may be produced from heat sources 202 to control pressure in the formation adjacent to the heat sources. Fluid produced from heat sources 202 may be transported through tubing or piping to collection piping 208 or the produced fluid may be transported through tubing or piping directly to treatment facilities 210. Treatment facilities 210 may include separation units, reaction units, upgrading units, fuel cells, turbines, storage vessels, and/or other systems and units for processing produced formation fluids. The treatment facilities may form transportation fuel from at least a portion of the hydrocarbons produced from the formation.

Temperature limited heaters may be in configurations and/or may include materials that provide automatic temperature limiting properties for the heater at certain temperatures. In certain embodiments, ferromagnetic materials are used in temperature limited heaters. Ferromagnetic material may self-limit temperature at or near the Curie temperature of the material to provide a reduced amount of heat at or near the Curie temperature when a time-varying current is applied to the material. In certain embodiments, the ferromagnetic material self-limits temperature of the temperature limited heater at a selected temperature that is approximately the Curie temperature. In certain embodiments, the selected temperature is within 35 °C, within 25 °C, within 20 °C, or within 10 °C of the Curie temperature. In certain embodiments, ferromagnetic materials are coupled with other materials (for example, highly conductive materials, high strength materials, corrosion resistant materials, or combinations thereof) to provide various electrical and/or mechanical properties. Some parts of the temperature limited heater may have a lower resistance (caused by different geometries and/or by using different ferromagnetic and/or non-ferromagnetic materials) than other parts of the temperature limited heater. Having parts of the temperature limited heater with various materials and/or dimensions allows for tailoring the desired heat output from each part of the heater.

Temperature limited heaters may be more reliable than other heaters. Temperature limited heaters may be less apt to break down or fail due to hot spots in the formation. In some embodiments, temperature limited heaters allow for substantially uniform heating of the formation. In some embodiments, temperature limited heaters are able to heat the formation more efficiently by operating at a higher average heat output along the entire length of the heater. The temperature limited heater operates at the higher average heat output along the entire length of the heater because power to the heater does not have to be reduced to the entire heater, as is the case with typical constant wattage heaters, if a temperature along any point of the heater exceeds, or is about to exceed, a maximum operating temperature of the heater. Heat output from portions of a temperature limited heater approaching a Curie temperature of the heater automatically reduces without controlled adjustment of the time-varying current applied to the heater. The heat output automatically reduces due to changes in electrical properties (for example, electrical resistance) of portions of the temperature limited heater. Thus, more power is supplied by the temperature limited heater during a greater portion of a heating process.

In certain embodiments, the system including temperature limited heaters initially provides a first heat output and then provides a reduced (second heat output) heat output, near, at, or above the Curie temperature of an electrically resistive portion of the heater when the temperature limited heater is energized by a time-varying current. The first heat output is the heat output at temperatures below which the temperature limited heater begins to self-limit. In some embodiments, the first heat output is the heat output at a temperature 50 °C, 75 °C, 100 °C, or 125 °C below the Curie temperature of the ferromagnetic material in the temperature limited heater.

The temperature limited heater may be energized by time-varying current (alternating current or modulated direct current) supplied at the wellhead. The wellhead may include a power source and other components (for example, modulation components, transformers, and/or capacitors) used in supplying power to the temperature limited heater. The temperature limited heater may be one of many heaters used to heat a portion of the formation.

In certain embodiments, the temperature limited heater includes a conductor that operates as a skin effect or proximity effect heater when time-varying current is applied to the conductor. The skin effect limits the depth of current penetration into the interior of the conductor. For ferromagnetic materials, the skin effect is dominated by the magnetic permeability of the conductor. The relative magnetic permeability of ferromagnetic materials is typically between 10 and 1000 (for example, the relative magnetic permeability of ferromagnetic materials is typically at least 10 and may be at least 50, 100, 500, 1000 or greater). As the temperature of the ferromagnetic material is raised above the Curie temperature and/or as the applied electrical current is increased, the magnetic permeability of the ferromagnetic material decreases substantially and the skin depth expands rapidly (for example, the skin depth expands as the inverse square root of the magnetic permeability). The reduction in magnetic permeability results in a decrease in the AC or modulated DC resistance of the conductor near, at, or above the Curie temperature and/or as the applied electrical current is increased. When the temperature limited heater is powered by a substantially constant current source, portions of the heater that approach, reach, or are above the Curie temperature may have reduced heat dissipation. Sections of the temperature limited heater that are not at or near the Curie temperature may be dominated by skin effect heating that allows the heater to have high heat dissipation due to a higher resistive load.

An advantage of using the temperature limited heater to heat hydrocarbons in the formation is that the conductor is chosen to have a Curie temperature in a desired range of temperature operation. Operation within the desired operating temperature range allows substantial heat injection into the formation while maintaining the temperature of the temperature limited heater, and other equipment, below design limit temperatures. Design limit temperatures are temperatures at which properties such as corrosion, creep, and/or deformation are adversely affected. The temperature limiting properties of the temperature limited heater inhibits overheating or burnout of the heater adjacent to low thermal conductivity "hot spots" in the formation. In some embodiments, the temperature limited heater is able to lower or control heat output and/or withstand heat at temperatures above 25 °C, 37 °C, 100 °C, 250 °C, 500 °C, 700 °C, 800 °C, 900 °C, or higher up to 1131 °C, depending on the materials used in the heater.

The temperature limited heater allows for more heat injection into the formation than constant wattage heaters because the energy input into the temperature limited heater does not have to be limited to accommodate low thermal conductivity regions adjacent to the heater. For example, in Green River oil shale there is a difference of at least a factor of 3 in the thermal conductivity of the lowest richness oil shale layers and the highest richness oil shale layers. When heating such a formation, substantially more heat is transferred to the formation with the temperature limited heater than with the conventional heater that is limited by the temperature at low thermal conductivity layers. The heat output along the entire length of the conventional heater needs to accommodate the low thermal conductivity layers so that the heater does not overheat at the low thermal conductivity layers and burn out. The heat output adjacent to the low thermal conductivity layers that are at high temperature will reduce for the temperature limited heater, but the remaining portions of the temperature limited heater that are not at high temperature will still provide high heat output. Because heaters for heating hydrocarbon formations typically have long lengths (for example, at least 10 m, 100 m, 300 m, at least 500 m, 1 km or more up to 10 km), the majority of the length of the temperature limited heater may be operating below the Curie temperature while only a few portions are at or near the Curie temperature of the temperature limited heater.

The use of temperature limited heaters allows for efficient transfer of heat to the formation. Efficient transfer of heat allows for reduction in time needed to heat the formation to a desired temperature. For the same heater spacing, temperature limited heaters may allow a larger average heat output while maintaining heater equipment temperatures below equipment design limit temperatures. Pyrolysis in the formation may occur at an earlier time with the larger average heat output provided by temperature limited heaters than the lower average heat output provided by constant wattage heaters. Temperature limited heaters counteract hot spots due to inaccurate well spacing or drilling where heater wells come too close together. In certain embodiments, temperature limited heaters allow for increased power output over time for heater wells that have been spaced too far apart, or limit power output for heater wells that are spaced too close together. Temperature limited heaters also supply more power in regions adjacent the overburden and underburden to compensate for temperature losses in these regions.

Temperature limited heaters may be advantageously used in many types of formations. For example, in tar sands formations or relatively permeable formations containing heavy hydrocarbons, temperature limited heaters may be used to provide a controllable low temperature output for reducing the viscosity of fluids, mobilizing fluids, and/or enhancing the radial flow of fluids at or near the wellbore or in the formation. Temperature limited heaters may be used to inhibit excess coke formation due to overheating of the near wellbore region of the formation.

The use of temperature limited heaters, in some embodiments, eliminates or reduces the need for expensive temperature control circuitry. For example, the use of temperature limited heaters eliminates or reduces the need to perform temperature logging and/or the need to use fixed thermocouples on the heaters to monitor potential overheating at hot spots.

In some embodiments, temperature limited heaters are more economical to manufacture or make than standard heaters. Typical ferromagnetic materials include iron, carbon steel, or ferritic stainless steel. Such materials are inexpensive as compared to nickel-based heating alloys (such as nichrome, Kanthal™ (Bulten-Kanthal AB, Sweden), and/or LOHM™ (Driver-Harris Company, Harrison, New Jersey, U.S.A.)) typically used in insulated conductor (mineral insulated cable) heaters. In one embodiment of the temperature limited heater, the temperature limited heater is manufactured in continuous lengths as an insulated conductor heater to lower costs and improve reliability.

Temperature limited heaters may be used for heating hydrocarbon formations including, but not limited to, oil shale formations, coal formations, tar sands formations, and heavy viscous oils. Temperature limited heaters may also be used in the field of environmental remediation to vaporize or destroy soil contaminants. Embodiments of temperature limited heaters may be used to heat fluids in a wellbore or sub-sea pipeline to inhibit deposition of paraffin or various hydrates. In some embodiments, a temperature limited heater is used for solution mining a subsurface formation (for example, an oil shale or a coal formation). In certain embodiments, a fluid (for example, molten salt) is placed in a wellbore and heated with a temperature limited heater to inhibit deformation and/or collapse of the wellbore. In some embodiments, the temperature limited heater is attached to a sucker rod in the wellbore or is part of the sucker rod itself. In some embodiments, temperature limited heaters are used to heat a near wellbore region to reduce near wellbore oil viscosity during production of high viscosity crude oils and during transport of high viscosity oils to the surface. In some embodiments, a temperature limited heater enables gas lifting of a viscous oil by lowering the viscosity of the oil without coking the oil. Temperature limited heaters may be used in sulfur transfer lines to maintain temperatures between 110 °C and 130 °C.

Certain embodiments of temperature limited heaters may be used in chemical or refinery processes at elevated temperatures that require control in a narrow temperature range to inhibit unwanted chemical reactions or damage from locally elevated temperatures. Some applications may include, but are not limited to, reactor tubes, cokers, and distillation towers. Temperature limited heaters may also be used in pollution control devices (for example, catalytic converters, and oxidizers) to allow rapid heating to a control temperature without complex temperature control circuitry. Additionally, temperature limited heaters may be used in food processing to avoid damaging food with excessive temperatures. Temperature limited heaters may also be used in the heat treatment of metals (for example, annealing of weld joints). Temperature limited heaters may also be used in floor heaters, cauterizers, and/or various other appliances. Temperature limited heaters may be used with biopsy needles to destroy tumors by raising temperatures in vivo.

Some embodiments of temperature limited heaters may be useful in certain types of medical and/or veterinary devices. For example, a temperature limited heater may be used to therapeutically treat tissue in a human or an animal. A temperature limited heater for a medical or veterinary device may have ferromagnetic material including a palladium-copper alloy with a Curie temperature of 50 °C. A high frequency (for example, a frequency greater than 1 MHz) may be used to power a relatively small temperature limited heater for medical and/or veterinary use.

The ferromagnetic alloy or ferromagnetic alloys used in the temperature limited heater determine the Curie temperature of the heater. Curie temperature data for various metals is listed in "American Institute of Physics Handbook," Second Edition, McGraw-Hill, pages 5-170 through 5-176. Ferromagnetic conductors may include one or more of the ferromagnetic elements (iron, cobalt, and nickel) and/or alloys of these elements. In some embodiments, ferromagnetic conductors include iron-chromium (Fe-Cr) alloys that contain tungsten (W) (for example, HCM12A and SAVE12 (Sumitomo Metals Co., Japan) and/or iron alloys that contain chromium (for example, Fe-Cr alloys, Fe-Cr-W alloys, Fe-Cr-V (vanadium) alloys, Fe-Cr-Nb (Niobium) alloys). Of the three main ferromagnetic elements, iron has a Curie temperature of approximately 770 °C; cobalt (Co) has a Curie temperature of approximately 1131 °C; and nickel has a Curie temperature of approximately 358 °C. An iron-cobalt alloy has a Curie temperature higher than the Curie temperature of iron. For example, iron-cobalt alloy with 2% by weight cobalt has a Curie temperature of approximately 800 °C; iron-cobalt alloy with 12% by weight cobalt has a Curie temperature of approximately 900 °C; and iron-cobalt alloy with 20% by weight cobalt has a Curie temperature of approximately 950 °C. Iron-nickel alloy has a Curie temperature lower than the Curie temperature of iron. For example, iron-nickel alloy with 20% by weight nickel has a Curie temperature of approximately 720 °C, and iron-nickel alloy with 60% by weight nickel has a Curie temperature of approximately 560 °C.

Some non-ferromagnetic elements used as alloys raise the Curie temperature of iron. For example, an iron-vanadium alloy with 5.9% by weight vanadium has a Curie temperature of approximately 815 °C. Other non-ferromagnetic elements (for example, carbon, aluminum, copper, silicon, and/or chromium) may be alloyed with iron or other ferromagnetic materials to lower the Curie temperature. Non-ferromagnetic materials that raise the Curie temperature may be combined with non-ferromagnetic materials that lower the Curie temperature and alloyed with iron or other ferromagnetic materials to produce a material with a desired Curie temperature and other desired physical and/or chemical properties. In some embodiments, the Curie temperature material is a ferrite such as $NiFe_2O_4$. In other embodiments, the Curie temperature material is a binary compound such as $FeNi_3$ or Fe_3Al.

Certain embodiments of temperature limited heaters may include more than one ferromagnetic material. Such embodiments are within the scope of embodiments described herein if any conditions described herein apply to at least one of the ferromagnetic materials in the temperature limited heater.

Ferromagnetic properties generally decay as the Curie temperature is approached. The "Handbook of Electrical Heating for Industry" by C. James Erickson (IEEE Press, 1995) shows a typical curve for 1% carbon steel (steel with 1% carbon by weight). The loss of magnetic permeability starts at temperatures above 650 °C and tends to be complete when temperatures exceed 730 °C. Thus, the self-limiting temperature may be somewhat below the actual Curie temperature of the ferromagnetic conductor. The skin depth for current flow in 1% carbon steel is 0.132 cm at room temperature and increases to 0.445 cm at 720 °C. From 720 °C to 730 °C, the skin depth sharply increases to over 2.5 cm. Thus, a temperature limited heater embodiment using 1% carbon steel begins to self-limit between 650 °C and 730 °C.

Skin depth generally defines an effective penetration depth of time-varying current into the conductive material. In general, current density decreases exponentially with distance from an outer surface to the center along the radius of the conductor. The depth at which the current density is approximately $1/e$ of the surface current density is called the skin depth. For a solid cylindrical rod with a diameter much greater than the penetration depth, or for hollow cylinders with a wall thickness exceeding the penetration depth, the skin depth, δ, is:

$$(1)\ \delta = 1981.5 * (\rho/(\mu * f))^{1/2};$$

in which:
δ = skin depth in inches;
ρ = resistivity at operating temperature (ohm-cm);
μ = relative magnetic permeability; and
f = frequency (Hz).

EQN. 1 is obtained from "Handbook of Electrical Heating for Industry" by C. James Erickson (IEEE Press, 1995). For most metals, resistivity (ρ) increases with temperature. The relative magnetic permeability generally varies with temperature and with current. Additional equations may be used to assess the variance of magnetic permeability and/or skin depth on both temperature and/or current. The dependence of μ on current arises from the dependence of μ on the magnetic field.

Materials used in the temperature limited heater may be selected to provide a desired turndown ratio. Turndown ratios of at least 1.1:1, 2:1, 3:1, 4:1, 5:1, 10:1, 30:1, or 50:1 may be selected for temperature limited heaters. Larger turndown ratios may also be used. A selected turndown ratio may depend on a number of factors including, but not limited to, the type of formation in which the temperature limited heater is located (for example, a higher turndown ratio may be used for an oil shale formation with large variations in thermal conductivity between rich and lean oil shale layers) and/or a temperature limit of materials used in the wellbore (for example, temperature limits of heater materials). In some embodiments, the turndown ratio is increased by coupling additional copper or another good electrical conductor to the ferromagnetic material (for example, adding copper to lower the resistance above the Curie temperature).

The temperature limited heater may provide a minimum heat output (power output) below the Curie temperature of the heater. In certain embodiments, the minimum heat output is at least 400 W/m (Watts per meter), 600 W/m, 700 W/m, 800 W/m, or higher up to 2000 W/m. The temperature limited heater reduces the amount of heat output by a section of the heater when the temperature of the section of the heater approaches or is above the Curie temperature. The reduced amount of heat may be substantially less than the heat output below the Curie temperature. In some embodiments, the reduced amount of heat is at most 400 W/m, 200 W/m, 100 W/m or may approach 0 W/m.

The AC or modulated DC resistance and/or the heat output of the temperature limited heater may decrease as the temperature approaches the Curie temperature and decrease sharply near or above the Curie temperature due to the Curie effect. In certain embodiments, the value of the electrical resistance or heat output above or near the Curie temperature is at most one-half of the value of electrical resistance or heat output at a certain point below the Curie temperature. In some embodiments, the heat output above or near the Curie temperature is at most 90%, 70%, 50%, 30%, 20%, 10%, or less (down to 1%) of the heat output at a certain point below the Curie temperature (for example, 30 °C below the Curie temperature, 40 °C below the Curie temperature, 50 °C below the Curie temperature, or 100 °C below the Curie temperature). In certain embodiments, the electrical resistance above or near the Curie temperature decreases to 80%, 70%, 60%, 50%, or less (down to 1%) of the electrical resistance at a certain point below the Curie temperature (for example, 30 °C below the Curie temperature, 40 °C below the Curie temperature, 50 °C below the Curie temperature, or 100 °C below the Curie temperature).

In some embodiments, AC frequency is adjusted to change the skin depth of the ferromagnetic material. For example, the skin depth of 1% carbon steel at room temperature is 0.132 cm at 60 Hz, 0.0762 cm at 180 Hz, and 0.046 cm at 440 Hz. Since heater diameter is typically larger than twice the skin depth, using a higher frequency (and thus a heater with a smaller diameter) reduces heater costs. For a fixed geometry, the higher frequency results in a higher turndown ratio. The turndown ratio at a higher frequency is calculated by multiplying the turndown ratio at a lower frequency by the square root of the higher frequency divided by the lower frequency. In some embodiments, a frequency between 100 Hz and 1000 Hz, between 140 Hz and 200 Hz, or between 400 Hz and 600 Hz is used (for example, 180 Hz, 540 Hz, or 720 Hz). In some embodiments, high frequencies may be used. The frequencies may be greater than 1000 Hz.

In certain embodiments, modulated DC (for example, chopped DC, waveform modulated DC, or cycled DC) may be used for providing electrical power to the temperature limited heater. A DC modulator or DC chopper may be coupled to a DC power supply to provide an output of modulated direct current. In some embodiments, the DC power supply may include means for modulating DC. One example of a DC modulator is a DC-to-DC converter system. DC-to-DC converter systems are generally known in the art. DC is typically modulated or chopped into a desired waveform. Waveforms for DC modulation include, but are not limited to, square-wave, sinusoidal, deformed sinusoidal, deformed square-wave, triangular, and other regular or irregular waveforms.

The modulated DC waveform generally defines the frequency of the modulated DC. Thus, the modulated DC waveform may be selected to provide a desired modulated DC frequency. The shape and/or the rate of modulation (such as the rate of chopping) of the modulated DC waveform may be varied to vary the modulated DC frequency. DC may be modulated at frequencies that are higher than generally available AC frequencies. For example, modulated DC may be provided at frequencies of at least 1000 Hz. Increasing the frequency of supplied current to higher values advantageously increases the turndown ratio of the temperature limited heater.

In certain embodiments, the modulated DC waveform is adjusted or altered to vary the modulated DC frequency. The DC modulator may be able to adjust or alter the modulated DC waveform at any time during use of the temperature limited heater and at high currents or voltages. Thus, modulated DC provided to the temperature limited heater is not limited to a single frequency or even a small set of frequency values. Waveform selection using the DC modulator typically allows for a wide range of modulated DC frequencies and for discrete control of the modulated DC frequency. Thus, the modulated DC frequency is more easily set at a distinct value whereas AC frequency is generally limited to multiples of the line frequency. Discrete control of the modulated DC frequency allows for more selective control over the turndown ratio of the temperature limited heater. Being able to selectively control the turndown ratio of the temperature limited heater allows for a broader range of materials to be used in designing and constructing the temperature limited heater.

In certain embodiments, the temperature limited heater includes a composite conductor with a ferromagnetic tubular and a non-ferromagnetic, high electrical conductivity core. The non-ferromagnetic, high electrical conductivity core reduces a required diameter of the conductor. The core or non-ferromagnetic conductor may be copper or copper alloy. The core or non-ferromagnetic conductor may also be made of other metals that exhibit low electrical resistivity and relative magnetic permeabilities near 1 (for example, substantially non-ferromagnetic materials such as aluminum and aluminum alloys, phosphor bronze, beryllium copper, and/or brass).

A composite conductor allows the electrical resistance of the temperature limited heater to decrease more steeply near the Curie temperature. As the skin depth increases near the Curie temperature to include the copper core, the electrical resistance decreases very sharply.

The composite conductor may increase the conductivity of the temperature limited heater and/or allow the heater to operate at lower voltages. In an embodiment, the composite conductor exhibits a relatively flat resistance versus temperature profile at temperatures below a region near the Curie temperature of the ferromagnetic conductor of the composite conductor. In some embodiments, the temperature limited heater exhibits a relatively flat resistance versus temperature profile between 100 °C and 750 °C or between 300 °C and 600 °C. The relatively flat resistance versus temperature profile may also be exhibited in other temperature ranges by adjusting, for example, materials and/or the configuration of materials in the temperature limited heater. In certain embodiments, the relative thickness of each material in the composite conductor is selected to produce a desired resistivity versus temperature profile for the temperature limited heater.

In certain embodiments, the relative thickness of each material in a composite conductor is selected to produce a desired resistivity versus temperature profile for a temperature limited heater.

A composite conductor (for example, a composite inner conductor or a composite outer conductor) may be manufactured by methods including, but not limited to, coextrusion, roll forming, tight fit tubing (for example, cooling the inner member and heating the outer member, then inserting the inner member in the outer member, followed by a drawing operation and/or allowing the system to cool), explosive or electromagnetic cladding, arc overlay welding, longitudinal strip welding, plasma powder welding, billet coextrusion, electroplating, drawing, sputtering, plasma deposition, coextrusion casting, magnetic forming, molten cylinder casting (of inner core material inside the outer or vice versa), insertion followed by welding or high temperature braising, shielded active gas welding (SAG), and/or insertion of an inner pipe in an outer pipe followed by mechanical expansion of the inner pipe by hydroforming or use of a pig to expand and swage the inner pipe against the outer pipe. In some embodiments, a ferromagnetic conductor is braided over a non-ferromagnetic conductor. In certain embodiments, composite conductors are formed using methods similar to those used for cladding (for example, cladding copper to steel). A metallurgical bond between copper cladding and base ferromagnetic material may be advantageous. Composite conductors produced by a coextrusion process that forms a good metallurgical bond (for example, a good bond between copper and 446 stainless steel) may be provided by Anomet Products, Inc. (Shrewsbury, Massachusetts, U.S.A.).

FIGS. 3-9 depict various embodiments of temperature limited heaters. One or more features of an embodiment of the temperature limited heater depicted in any of these figures may be combined with one or more features of other embodiments of temperature limited heaters depicted in these figures. In certain embodiments described herein, temperature limited heaters are dimensioned to operate at a frequency of 60 Hz AC. It is to be understood that dimensions of the temperature limited heater may be adjusted from those described herein in order for the temperature limited heater to operate in a similar manner at other AC frequencies or with modulated DC current.

FIG. 3 depicts a cross-sectional representation of an embodiment of the conductor-in-conduit heater. Conductor 212 is disposed in conduit 214. Conductor 212 is a rod or conduit of electrically conductive material. Low resistance sections 218 are present at both ends of conductor 212 to generate less heating in these sections. Low resistance section 218 is formed by having a greater cross-sectional area of conductor 212 in that section, or the sections are made of material having less resistance. In certain embodiments, low resistance section 218 includes a low resistance conductor coupled to conductor 212.

Conduit 214 is made of an electrically conductive material. Conduit 214 is disposed in opening 216 in hydrocarbon layer 220. Opening 216 has a diameter that accommodates conduit 214.

Conductor 212 may be centered in conduit 214 by centralizers 222. Centralizers 222 electrically isolate conductor 212 from conduit 214. Centralizers 222 inhibit movement and properly locate conductor 212 in conduit 214. Centralizers 222 are made of ceramic material or a combination of ceramic and metallic materials. Centralizers 222 inhibit deformation of conductor 212 in conduit 214. Centralizers 222 are touching or spaced at intervals between approximately 0.1 m (meters) and approximately 3 m or more along conductor 212.

A second low resistance section 218 of conductor 212 may couple conductor 212 to wellhead 224, as depicted in FIG. 3. Electrical current may be applied to conductor 212 from power cable 226 through low resistance section 218 of conductor 212. Electrical current passes from conductor 212 through sliding connector 228 to conduit 214. Conduit 214 may be electrically insulated from overburden casing 230 and from wellhead 224 to return electrical current to power cable 226. Heat may be generated in conductor 212 and conduit 214. The generated heat may radiate in conduit 214 and opening 216 to heat at least a portion of hydrocarbon layer 220.

Overburden casing 230 may be disposed in overburden 232. Overburden casing 230 is, in some embodiments, surrounded by materials (for example, reinforcing material and/or cement) that inhibit heating of overburden 232. Low resistance section 218 of conductor 212 may be placed in overburden casing 230. Low resistance section 218 of conductor 212 is made of, for example, carbon steel. Low resistance section 218 of conductor 212 may be centralized in overburden casing 230 using centralizers 222. Centralizers 222 are spaced at intervals of approximately 6 m to approximately 12 m or, for example, approximately 9 m along low resistance section 218 of conductor 212. In a heater embodiment, low resistance section 218 of conductor 212 is coupled to conductor 212 by one or more welds. In other heater embodiments, low resistance sections are threaded, threaded and welded, or otherwise coupled to the conductor. Low resistance section 218 generates little or no heat in overburden casing 230. Packing 234 may be placed between overburden casing 230 and opening 216. Packing 234 may be used as a cap at the junction of overburden 232 and hydrocarbon layer 220 to allow filling of materials in the annulus between overburden casing 230 and opening 216. In some embodiments, packing 234 inhibits fluid from flowing from opening 216 to surface 236.

FIG. 4 depicts a cross-sectional representation of an embodiment of a removable conductor-in-conduit heat source. Conduit 214 may be placed in opening 216 through overburden 232 such that a gap remains between the conduit and overburden casing 230. Fluids may be removed from opening 216 through the gap between conduit 214 and overburden casing 230. Fluids may be removed from the gap through conduit 238. Conduit 214 and components of the heat source included in the conduit that are coupled to wellhead 224 may be removed from opening 216 as a single unit. The heat source may be removed as a single unit to be repaired, replaced, and/or used in another portion of the formation.

For a temperature limited heater in which the ferromagnetic conductor provides a majority of the resistive heat output below the Curie temperature, a majority of the current flows through material with highly non-linear functions of magnetic field (H) versus magnetic induction (B). These non-linear functions may cause strong inductive effects and distortion that lead to decreased power factor in the temperature limited heater at temperatures below the Curie temperature. These effects may render the electrical power supply to the temperature limited heater difficult to control and may result in additional current flow through surface and/or overburden power supply conductors. Expensive and/or difficult to implement control systems such as variable capacitors or modulated power supplies may be used to attempt to compensate for these effects and to control temperature limited heaters where the majority of the resistive heat output is provided by current flow through the ferromagnetic material.

In certain temperature limited heater embodiments, the ferromagnetic conductor confines a majority of the flow of electrical current to an electrical conductor coupled to the ferromagnetic conductor when the temperature limited heater is below or near the Curie temperature of the ferromagnetic conductor. The electrical conductor may be a sheath, jacket, support member, corrosion resistant member, or other electrically resistive member. In some embodiments, the ferromagnetic conductor confines a majority of the flow of electrical current to the electrical conductor positioned between an outermost layer and the ferromagnetic conductor. The ferromagnetic conductor is located in the cross section of the temperature limited heater such that the magnetic properties of the ferromagnetic conductor at or below the Curie temperature of the ferromagnetic conductor confine the majority of the flow of electrical current to the electrical conductor. The majority of the flow of electrical current is confined to the electrical conductor due to the skin effect of the ferromagnetic conductor. Thus, the majority of the current is flowing through material with substantially linear resistive properties throughout most of the operating range of the heater.

In certain embodiments, the ferromagnetic conductor and the electrical conductor are located in the cross section of the temperature limited heater so that the skin effect of the ferromagnetic material limits the penetration depth of electrical current in the electrical conductor and the ferromagnetic conductor at temperatures below the Curie temperature of the ferromagnetic conductor. Thus, the electrical conductor provides a majority of the electrically resistive heat output of the temperature limited heater at temperatures up to a temperature at or near the Curie temperature of the ferromagnetic conductor. In certain embodiments, the dimensions of the electrical conductor may be chosen to provide desired heat output characteristics.

Because the majority of the current flows through the electrical conductor below the Curie temperature, the temperature limited heater has a resistance versus temperature profile that at least partially reflects the resistance versus temperature profile of the material in the electrical conductor. Thus, the resistance versus temperature profile of the temperature limited heater is substantially linear below the Curie temperature of the ferromagnetic conductor if the material in the electrical conductor has a substantially linear resistance versus temperature profile. For example, the temperature limited heater in which the majority of the current flows in the electrical conductor below the Curie temperature may have a resistance versus temperature profile similar to the profile shown in FIG. 11. The resistance of the temperature limited heater has little or no dependence on the current flowing through the heater until the temperature nears the Curie temperature. The majority of the current flows in the electrical conductor rather than the ferromagnetic conductor below the Curie temperature.

Resistance versus temperature profiles for temperature limited heaters in which the majority of the current flows in the electrical conductor also tend to exhibit sharper reductions in resistance near or at the Curie temperature of the ferromagnetic conductor. The sharper reductions in resistance near or at the Curie temperature are easier to control than more gradual resistance reductions near the Curie temperature.

In certain embodiments, the material and/or the dimensions of the material in the electrical conductor are selected so that the temperature limited heater has a desired resistance versus temperature profile below the Curie temperature of the ferromagnetic conductor.

Temperature limited heaters in which the majority of the current flows in the electrical conductor rather than the ferromagnetic conductor below the Curie temperature are easier to predict and/or control. Behavior of temperature limited heaters in which the majority of the current flows in the electrical conductor rather than the ferromagnetic conductor below the Curie temperature may be predicted by, for example, its resistance versus temperature profile and/or its power factor versus temperature profile. Resistance versus temperature profiles and/or power factor versus temperature profiles may be assessed or predicted by, for example, experimental measurements that assess the behavior of the temperature limited heater, analytical equations that assess or predict the behavior of the temperature limited heater, and/or simulations that assess or predict the behavior of the temperature limited heater.

In certain embodiments, assessed or predicted behavior of the temperature limited heater is used to control the temperature limited heater. The temperature limited heater may be controlled based on measurements (assessments) of the resistance and/or the power factor during operation of the heater. In some embodiments, the power, or current, supplied to the temperature limited heater is controlled based on assessment of the resistance and/or the power factor of the heater during operation of the heater and the comparison of this assessment versus the predicted behavior of the heater. In certain embodiments, the temperature limited heater is controlled without measurement of the temperature of the heater or a temperature near the heater. Controlling the temperature limited heater without temperature measurement eliminates operating costs associated with downhole temperature measurement. Controlling the temperature limited heater based on assessment of the resistance and/or the power factor of the heater also reduces the time for making adjustments in the power or current supplied to the heater compared to controlling the heater based on measured temperature.

As the temperature of the temperature limited heater approaches or exceeds the Curie temperature of the ferromagnetic conductor, reduction in the ferromagnetic properties of the ferromagnetic conductor allows electrical current to flow through a greater portion of the electrically conducting cross section of the temperature limited heater. Thus, the electrical resistance of the temperature limited heater is reduced and the temperature limited heater automatically provides reduced heat output at or near the Curie temperature of the ferromagnetic conductor. In certain embodiments, a highly electrically conductive member is coupled to the ferromagnetic conductor and the electrical conductor to reduce the electrical resistance of the temperature limited heater at or above the Curie temperature of the ferromagnetic conductor. The highly electrically conductive member may be an inner conductor, a core, or another conductive member of copper, aluminum, nickel, or alloys thereof.

The ferromagnetic conductor that confines the majority of the flow of electrical current to the electrical conductor at temperatures below the Curie temperature may have a relatively small cross section compared to the ferromagnetic conductor in temperature limited heaters that use the ferromagnetic conductor to provide the majority of resistive heat output up to or near the Curie temperature. A temperature limited heater that uses the electrical conductor to provide a majority of the resistive heat output below the Curie temperature has low magnetic inductance at temperatures below the Curie temperature because less current is flowing through the ferromagnetic conductor as compared to the temperature limited heater where the majority of the resistive heat output below the Curie temperature is provided by the ferromagnetic material. Magnetic field (H) at radius (r) of the ferromagnetic conductor is proportional to the current (I) flowing through the ferromagnetic conductor and the core divided by the radius, or:

(2) $H \propto I/r$.

Since only a portion of the current flows through the ferromagnetic conductor for a temperature limited heater that uses the outer conductor to provide a majority of the resistive heat output below the Curie temperature, the magnetic field of the temperature limited heater may be significantly smaller than the magnetic field of the temperature limited heater where the majority of the current flows through the ferromagnetic material. The relative magnetic permeability (μ) may be large for small magnetic fields.

The skin depth (δ) of the ferromagnetic conductor is inversely proportional to the square root of the relative magnetic permeability (μ):

(3) $\delta \propto (1/\mu)^{1/2}$.

Increasing the relative magnetic permeability decreases the skin depth of the ferromagnetic conductor. However, because only a portion of the current flows through the ferromagnetic conductor for temperatures below the Curie temperature, the radius (or thickness) of the ferromagnetic conductor may be decreased for ferromagnetic materials with large relative magnetic permeabilities to compensate for the decreased skin depth while still allowing the skin effect to limit the penetration depth of the electrical current to the electrical conductor at temperatures below the Curie temperature of the ferromagnetic conductor. The radius (thickness) of the ferromagnetic conductor may be between 0.3 mm and 8 mm, between 0.3 mm and 2 mm, or between 2 mm and 4 mm depending on the relative magnetic permeability of the ferromagnetic conductor. Decreasing the thickness of the ferromagnetic conductor decreases costs of manufacturing the temperature limited heater, as the cost of ferromagnetic material tends to be a significant portion of the cost of the temperature limited heater. Increasing the relative magnetic permeability of the ferromagnetic conductor provides a higher turndown ratio and a sharper decrease in electrical resistance for the temperature limited heater at or near the Curie temperature of the ferromagnetic conductor.

Ferromagnetic materials (such as purified iron or iron-cobalt alloys) with high relative magnetic permeabilities (for example, at least 200, at least 1000, at least 1×10^4, or at least 1×10^5) and/or high Curie temperatures (for example, at least 600 °C, at least 700 °C, or at least 800 °C) tend to have less corrosion resistance and/or less mechanical strength at high temperatures. The electrical conductor may provide corrosion resistance and/or high mechanical strength at high temperatures for the temperature limited heater. Thus, the ferromagnetic conductor may be chosen primarily for its ferromagnetic properties.

Confining the majority of the flow of electrical current to the electrical conductor below the Curie temperature of the ferromagnetic conductor reduces variations in the power factor. Because only a portion of the electrical current flows through the ferromagnetic conductor below the Curie temperature, the non-linear ferromagnetic properties of the ferromagnetic conductor have little or no effect on the power factor of the temperature limited heater, except at or near the Curie temperature. Even at or near the Curie temperature, the effect on the power factor is reduced compared to temperature limited heaters in which the ferromagnetic conductor provides a majority of the resistive heat output below the Curie temperature. Thus, there is less or no need for external compensation (for example, variable capacitors or waveform modification) to adjust for changes in the inductive load of the temperature limited heater to maintain a relatively high power factor.

In certain embodiments, the temperature limited heater, which confines the majority of the flow of electrical current to the electrical conductor below the Curie temperature of the ferromagnetic conductor, maintains the power factor above 0.85, above 0.9, or above 0.95 during use of the heater. Any reduction in the power factor occurs only in sections of the temperature limited heater at temperatures near the Curie temperature. Most sections of the temperature limited heater are typically not at or near the Curie temperature during use. These sections have a high power factor that approaches 1.0. The power factor for the entire temperature limited heater is maintained above

0.85, above 0.9, or above 0.95 during use of the heater even if some sections of the heater have power factors below 0.85.

Maintaining high power factors also allows for less expensive power supplies and/or control devices such as solid state power supplies or SCRs (silicon controlled rectifiers). These devices may fail to operate properly if the power factor varies by too large an amount because of inductive loads. With the power factors maintained at the higher values; however, these devices may be used to provide power to the temperature limited heater. Solid state power supplies also have the advantage of allowing fine tuning and controlled adjustment of the power supplied to the temperature limited heater.

In some embodiments, transformers are used to provide power to the temperature limited heater. Multiple voltage taps may be made into the transformer to provide power to the temperature limited heater. Multiple voltage taps allows the current supplied to switch back and forth between the multiple voltages. This maintains the current within a range bound by the multiple voltage taps.

The highly electrically conductive member, or inner conductor, increases the turndown ratio of the temperature limited heater. In certain embodiments, thickness of the highly electrically conductive member is increased to increase the turndown ratio of the temperature limited heater. In some embodiments, the thickness of the electrical conductor is reduced to increase the turndown ratio of the temperature limited heater. In certain embodiments, the turndown ratio of the temperature limited heater is between 1.1 and 10, between 2 and 8, or between 3 and 6 (for example, the turndown ratio is at least 1.1, at least 2, or at least 3).

FIG. 5 depicts an embodiment of a temperature limited heater in which the support member provides a majority of the heat output below the Curie temperature of the ferromagnetic conductor. Core 240 is an inner conductor of the temperature limited heater. In certain embodiments, core 240 is a highly electrically conductive material such as copper or aluminum. In some embodiments, core 240 is a copper alloy that provides mechanical strength and good electrically conductivity such as a dispersion strengthened copper. In one embodiment, core 240 is Glidcop® (SCM Metal Products, Inc., Research Triangle Park, North Carolina, U.S.A.). Ferromagnetic conductor 242 is a thin layer of ferromagnetic material between electrical conductor 244 and core 240. In certain embodiments, electrical conductor 244 is also support member 248. In certain embodiments, ferromagnetic conductor 242 is iron or an iron alloy. In some embodiments, ferromagnetic conductor 242 includes ferromagnetic material with a high relative magnetic permeability. For example, ferromagnetic conductor 242 may be purified iron such as Armco ingot iron (AK Steel Ltd., United Kingdom). Iron with some impurities typically has a relative magnetic permeability on the order of 400. Purifying the iron by annealing the iron in hydrogen gas (H_2) at 1450 °C increases the relative magnetic permeability of the iron. Increasing the relative magnetic permeability of ferromagnetic conductor 242 allows the thickness of the ferromagnetic conductor to be reduced. For example, the thickness of unpurified iron may be approximately 4.5 mm while the thickness of the purified iron is approximately 0.76 mm.

In certain embodiments, electrical conductor 244 provides support for ferromagnetic conductor 242 and the temperature limited heater. Electrical conductor 244 may be made of a material that provides good mechanical strength at temperatures near or above the Curie temperature of ferromagnetic conductor 242. In certain embodiments, electrical conductor 244 is a corrosion resistant member. Electrical conductor 244 (support member 248) may provide support for ferromagnetic conductor 242 and corrosion resistance. Electrical conductor 244 is made from a material that provides desired electrically resistive heat output at temperatures up to and/or above the Curie temperature of ferromagnetic conductor 242.

In an embodiment, electrical conductor 244 is 347H stainless steel. In some embodiments, electrical conductor 244 is another electrically conductive, good mechanical strength, corrosion resistant material. For example, electrical conductor 244 may be 304H, 316H, 347HH, NF709, Incoloy® 800H alloy (Inco Alloys International, Huntington, West Virginia, U.S.A.), Haynes® HR120® alloy, or Inconel® 617 alloy.

In some embodiments, electrical conductor 244 (support member 248) includes different alloys in different portions of the temperature limited heater. For example, a lower portion of electrical conductor 244 (support member 248) is 347H stainless steel and an upper portion of the electrical conductor (support member) is NF709. In certain embodiments, different alloys are used in different portions of the electrical conductor (support member) to increase the mechanical strength of the electrical conductor (support member) while maintaining desired heating properties for the temperature limited heater.

In some embodiments, ferromagnetic conductor 242 includes different ferromagnetic conductors in different portions of the temperature limited heater. Different ferromagnetic conductors may be used in different portions of the temperature limited heater to vary the Curie temperature and, thus, the maximum operating temperature in the different portions. In some embodiments, the Curie temperature in an upper portion of the temperature limited heater is lower than the Curie temperature in a lower portion of the heater. The lower Curie temperature in the upper portion increases the creep-rupture strength lifetime in the upper portion of the heater.

In the embodiment depicted in FIG. 5, ferromagnetic conductor 242, electrical conductor 244, and core 240 are dimensioned so that the skin depth of the ferromagnetic conductor limits the penetration depth of the majority of the flow of electrical current to the support member when the temperature is below the Curie temperature of the ferromagnetic conductor. Thus, electrical conductor 244 provides a majority of the electrically resistive heat output of the temperature limited heater at temperatures up to a temperature at or near the Curie temperature of ferromagnetic conductor 242. In certain embodiments, the temperature limited heater depicted in FIG. 5 is smaller (for example, an outside diameter of 3 cm, 2.9 cm, 2.5 cm, or less) than other temperature limited heaters that do not use electrical conductor 244 to provide the majority of electrically resistive heat output. The temperature limited heater depicted in FIG. 5 may be smaller because ferromagnetic conductor 242 is thin as compared to the size of the ferromagnetic conductor needed for a temperature limited heater in which the majority of the resistive heat output is provided by the ferromagnetic conductor.

In some embodiments, the support member and the corrosion resistant member are different members in the temperature limited heater. FIGS. 6 and 7 depict embodiments of temperature limited heaters in which the jacket provides a majority of the heat output below the Curie temperature of the ferromagnetic conductor. In these embodiments, electrical conductor 244 is jacket 246. Electrical conductor 244, ferromagnetic conductor 242, support member 248, and core 240 (in FIG. 6) or inner conductor 252 (in FIG. 7) are dimensioned so that the skin depth of the ferromagnetic conductor limits the penetration depth of the majority of the flow of electrical current to the thickness of the jacket. In certain embodiments, electrical conductor 244 is a material that is corrosion resistant and provides electrically resistive heat output below the Curie temperature of ferromagnetic conductor 242. For example, electrical conductor 244 is 825 stainless steel or 347H stainless steel. In some embodiments, electrical conductor 244 has a small thickness (for example, on the order of 0.5 mm).

In FIG. 6, core 240 is highly electrically conductive material such as copper or aluminum. Support member 248 is 347H stainless steel or another material with good mechanical strength at or near the Curie temperature of ferromagnetic conductor 242.

In FIG. 7, support member 248 is the core of the temperature limited heater and is 347H stainless steel or another material with good mechanical strength at or near the Curie temperature of ferromagnetic conductor 242. Inner conductor 252 is highly electrically conductive material such as copper or aluminum.

FIG. 8A and FIG. 8B depict cross-sectional representations of an embodiment of the temperature limited heater with triaxial conductors in which middle conductor 250 includes an electrical conductor in addition to the ferromagnetic material. The electrical conductor may be on the outside of middle conductor 250. The electrical conductor and the ferromagnetic material are dimensioned so that the skin depth of the ferromagnetic material limits the penetration depth of the majority of the flow of electrical current to the electrical conductor when the temperature is below the Curie temperature of the ferromagnetic material. The electrical conductor provides a majority of the electrically resistive heat output of middle conductor 250 (and the triaxial temperature limited heater) at temperatures up to a temperature at or near the Curie temperature of ferromagnetic conductor. The electrical conductor is made from a material that provides desired electrically resistive heat output at temperatures up to and/or above the Curie temperature of ferromagnetic member. For example, the electrical conductor is 347H stainless steel, 304H, 316H, 347HH, NF709, Incoloy® 800H alloy, Haynes® HR120® alloy, or Inconel® 617 alloy.

In certain embodiments, the materials and design of the temperature limited heater are chosen to allow use of the heater at high temperatures (for example, above 850 °C). FIG. 9 depicts a high temperature embodiment of the temperature limited heater. The heater depicted in FIG. 9 operates as a conductor-in-conduit heater with the majority of heat being generated in conduit 214. The conductor-in-conduit heater may provide a higher heat output because the majority of heat is generated in conduit 214 rather than conductor 212. Having the heat generated in conduit 214 reduces heat losses associated with transferring heat between the conduit and conductor 212.

Core 240 and conductive layer 254 are copper. In some embodiments, core 240 and conductive layer 254 are nickel if the operating temperatures is to be near or above the melting point of copper. Support members 248 are electrically conductive materials with good mechanical strength at high temperatures. Materials for support members 248 that withstand at least a maximum temperature of 870 °C may be, but are not limited to, MO-RE® alloys (Duraloy Technologies, Inc. (Scottdale, Pennsylvania, U.S.A.)), CF8C+ (Metaltek Intl. (Waukesha, Wisconsin, U.S.A.)), or Inconel® 617 alloy. Materials for support members 248 that withstand at least a maximum temperature of 980 °C include, but are not limited to, Incoloy® Alloy MA 956. Support member 248 in conduit 214 provides mechanical support for the conduit. Support member 248 in conductor 212 provides mechanical support for core 240.

Electrical conductor 244 is a thin corrosion resistant material. In certain embodiments, electrical conductor 244 is 347H, 617, 625, or 800H stainless steel. Ferromagnetic conductor 242 is a high Curie temperature ferromagnetic material such as iron-cobalt alloy (for example, a 15 % by weight cobalt, iron-cobalt alloy).

In certain embodiments, electrical conductor 244 provides the majority of heat output of the temperature limited heater at temperatures up to a temperature at or near the Curie temperature of ferromagnetic conductor 242. Conductive layer 254 increases the turndown ratio of the temperature limited heater.

In some embodiments, the temperature limited heater is used to achieve lower temperature heating (for example, for heating fluids in a production well, heating a surface pipeline, or reducing the viscosity of fluids in a wellbore or near wellbore region). Varying the ferromagnetic materials of the temperature limited heater allows for lower temperature heating. In some embodiments, the ferromagnetic conductor is made of material with a lower Curie temperature than that of 446 stainless steel. For example, the ferromagnetic conductor may be an alloy of iron and nickel. The alloy may have between 30% by weight and 42% by weight nickel with the rest being iron. In one embodiment, the alloy is Invar 36. Invar 36 is 36% by weight nickel in iron and has a Curie temperature of 277 °C. In some embodiments, an alloy is a three component alloy with, for example, chromium, nickel, and iron. For example, an alloy may have 6% by weight chromium, 42% by weight nickel, and 52% by weight iron. A 2.5 cm diameter rod of Invar 36 has a turndown ratio of approximately 2 to 1 at the Curie temperature. Placing the Invar 36 alloy over a copper core may allow for a smaller rod diameter. A copper core may result in a high turndown ratio. The insulator in lower temperature heater embodiments may be made of a high performance polymer insulator (such as PFA or PEEK™) when used with alloys with a Curie temperature that is below the melting point or softening point of the polymer insulator.

Examples

Non-restrictive examples are set forth below.

A 6 foot temperature limited heater element was placed in a 6 foot 347H stainless steel canister. The heater element was connected to the canister in a series configuration. The heater element and canister were placed in an oven. The oven was used to raise the temperature of the heater element and the canister. At varying temperatures, a series of electrical currents were passed through the heater element and returned through the canister. The resistance of the heater element and the power factor of the heater element were determined from measurements during passing of the electrical currents.

FIG. 10 depicts experimentally measured electrical resistance (mΩ) versus temperature (°C) at several currents for a temperature limited heater with a copper core, a carbon steel ferromagnetic conductor, and a 347H stainless steel support member. The ferromagnetic conductor was a low-carbon steel with a Curie temperature of 770 °C. The ferromagnetic conductor was sandwiched between the copper core and the 347H support member. The copper core had a diameter of 0.5". The ferromagnetic conductor had an outside diameter of 0.765". The support member had an outside diameter of 1.05". The canister was a 3" Schedule 160 347H stainless steel canister.

Data 256 depicts electrical resistance versus temperature for 300 A at 60 Hz AC applied current. Data 258 depicts resistance versus temperature for 400A at 60 Hz AC applied current. Data 260 depicts resistance versus temperature for 500A at 60 Hz AC applied current. Curve 262 depicts resistance versus temperature for 10A DC applied current. The resistance versus temperature data indicates that the AC resistance of the temperature limited heater linearly increased up to a temperature near the Curie temperature of the ferromagnetic conductor. Near the Curie temperature, the AC resistance decreased rapidly until the AC resistance equaled the DC resistance above the Curie temperature. The linear dependence of the AC resistance below the Curie temperature at least partially reflects the linear dependence of the AC resistance of 347H at these temperatures. Thus, the linear dependence of the AC resistance below the Curie temperature indicates that the majority of the current is flowing through the 347H support member at these temperatures.

FIG. 11 depicts experimentally measured electrical resistance (mΩ) versus temperature (°C) data at several currents for a temperature limited heater with a copper core, a iron-cobalt ferromagnetic conductor, and a 347H stainless steel support member. The iron-cobalt ferromagnetic conductor was an iron-cobalt conductor with 6% cobalt by weight and a Curie temperature of 834 °C. The ferromagnetic conductor was sandwiched between the copper core and the 347H support member. The copper core had a diameter of 0.465". The ferromagnetic conductor had an outside diameter of 0.765". The support member had an outside diameter of 1.05". The canister was a 3" Schedule 160 347H stainless steel canister.

Data 264 depicts resistance versus temperature for 100 A at 60 Hz AC applied current. Data 266 depicts resistance versus temperature for 400 A at 60 Hz AC applied current. Curve 268 depicts resistance versus temperature for 10A DC. The AC resistance of this temperature limited heater turned down at a higher temperature than the previous temperature limited heater. This was due to the added cobalt increasing the Curie temperature of the ferromagnetic conductor. The AC resistance was substantially the same as the AC resistance of a tube of 347H steel having the dimensions of the support member. This indicates that the majority of the current is flowing through the 347H support member at these temperatures. The resistance curves in FIG. 11 are generally the same shape as the resistance curves in FIG. 10.

FIG. 12 depicts experimentally measured power factor (y-axis) versus temperature (°C) at two AC currents for the temperature limited heater with the copper core, the iron-cobalt ferromagnetic conductor, and the 347H stainless steel support member. Curve 270 depicts power factor versus temperature for 100A at 60 Hz AC applied current. Curve 272 depicts power factor versus temperature for 400A at 60 Hz AC applied current. The power factor was close to unity (1) except for the region around the Curie temperature. In the region around the Curie temperature, the non-linear magnetic properties and a larger portion of the current flowing through the ferromagnetic conductor produce inductive effects and distortion in the heater that lowers the power factor. FIG. 12 shows that the minimum value of the power factor for this heater remained above 0.85 at all temperatures in the experiment. Because only portions of the temperature limited heater used to heat a subsurface formation may be at the Curie temperature at any given point in time and the power factor for these portions does not go below 0.85 during use, the power factor for the entire temperature limited heater would remain above 0.85 (for example, above 0.9 or above 0.95) during use.

From the data in the experiments for the temperature limited heater with the copper core, the iron-cobalt ferromagnetic conductor, and the 347H stainless steel support member, the turndown ratio (y-axis) was calculated as a function of the maximum power (W/m) delivered by the temperature limited heater. The results of these calculations are depicted in FIG. 13. The curve in FIG. 13 shows that the turndown ratio (y-axis) remains above 2 for heater powers up to approximately 2000 W/m. This curve is used to determine the ability of a heater to effectively provide heat output in a sustainable manner. A temperature limited heater with the curve similar to the curve in FIG. 13 would be able to provide sufficient heat output while maintaining temperature limiting properties that inhibit the heater from overheating or malfunctioning.

A theoretical model has been used to predict the experimental results. The theoretical model is based on an analytical solution for the AC resistance of a composite conductor. The composite conductor has a thin layer of ferromagnetic material, with a relative magnetic permeability $\mu_2/\mu_0 >> 1$, sandwiched between two non-ferromagnetic materials, whose relative magnetic permeabilities, μ_1/μ_0 and μ_3/μ_0, are close to unity and within which skin effects are negligible. An assumption in the model is that the ferromagnetic material is treated as linear. In addition, the way in which the relative magnetic permeability, μ_2/μ_0, is extracted from magnetic data for use in the model is far from rigorous.

In the theoretical model, the three conductors, from innermost to outermost, have radii $a < b < c$ with electrical conductivities σ_1, σ_2, and σ_3, respectively. The electric and magnetic fields everywhere are of the harmonic form:

Electric fields:

(7) $E_1(r,t) = E_{S1}(r)e^{j\omega t}; r < a$;

(8) $E_2(r,t) = E_{S2}(r)e^{j\omega t}; a < r < b$; and

(9) $E_3(r,t) = E_{S3}(r)e^{j\omega t}; b < r < c$.

Magnetic fields:

(10) $H_1(r,t) = H_{S1}(r)e^{j\omega t}; r < a$;

(11) $H_2(r,t) = H_{S2}(r)e^{j\omega t}; a < r < b$; and

(12) $H_3(r,t) = H_{S3}(r)e^{j\omega t}; b < r < c$.

The boundary conditions satisfied at the interfaces are:

(13) $E_{S1}(a) = E_{S2}(a); H_{S1}(a) = H_{S2}(a)$; and

(14) $E_{S2}(b) = E_{S3}(b); H_{S2}(b) = H_{S3}(b)$.

Current flows uniformly in the non-Curie conductors, so that:

(15) $H_{S1}(a) = J_{S1}(a)(a/2) = \frac{1}{2}a\sigma_1 E_{S1}(a)$; and

(16) $I - 2\pi b H_{S3}(b) = \pi(c^2 - b^2)J_{S3}(b) = \pi(c^2 - b^2)\sigma_3 E_{S3}(b)$.

I denotes the total current flowing through the composite conductor sample. EQNS. 13 and 14 are used to express EQNS. 15 and 16 in terms of boundary conditions pertaining to material 2 (the ferromagnetic material). This yields:

(17) $H_{S2}(a) = \frac{1}{2}a\sigma_1 E_{S2}(a)$; and

(18) $I = 2\pi b H_{S2}(b) + \pi(c^2 - b^2)\sigma_3 E_{S2}(b)$.

$E_{S2}(r)$ satisfies the equation:

(19) $$\frac{1}{r}\frac{d}{dr}\left(r\frac{dE_{S2}}{dr}\right) - C^2 E_{S2} = 0,$$

with

(20) $C^2 = j\omega\mu_2\sigma_2$.

Using the fact that:

(21) $$H_{S2}(r) = \frac{j}{\mu_2\omega}\frac{dE_{S2}}{dr};$$

the boundary conditions in EQNS. 17 and 18 are expressed in terms of E_{S2} and its derivatives as follows:

(22) $$\left.\frac{j}{\mu_2\omega}\frac{dE_{S2}}{dr}\right|_a = \tfrac{1}{2}a\sigma_1 E_{S2}(a);$$ and

(23) $$I = 2\pi b\left.\frac{j}{\mu_2\omega}\frac{dE_{S2}}{dr}\right|_b + \pi(c^2 - b^2)\sigma_3 E_{S2}(b).$$

The non-dimensional coordinate, χ, is introduced via the equation:

(24) $$r = \tfrac{1}{2}(a+b)\left\{1 + \frac{b-a}{a+b}\chi\right\}.$$

χ is −1 for $r = a$, and χ is 1 for $r = b$. EQN. 19 is written in terms of χ as:

(25) $(1+\beta\chi)^{-1}\frac{d}{d\chi}\left\{(1+\beta\chi)\frac{dE_{S2}}{d\chi}\right\}-\alpha^2\chi=0$,

with

(26) $\alpha=\frac{1}{2}(b-a)C$; and

(27) $\beta=(b-a)/(b+a)$.

α can be expressed as:

(28) $\alpha=\alpha_R(1-i)$,

with

(29) $\alpha_R{}^2=\frac{1}{8}(b-a)^2\mu_2\sigma_2\omega=\frac{1}{4}(b-a)^2/\delta^2$.

EQNS. 22 and 23 are expressed as:

(30) $\left.\frac{d}{d\chi}\right|_{-1} E_a=-j\gamma_a E_a$; and

(31) $\left.\frac{d}{d\chi}\right|_{1} E_b=j\gamma_b E_b-j\tilde{I}$.

In EQNS. 30 and 31, the short-hand notation E_a and E_b is used for $E_{S2}(a)$ and $E_{S2}(b)$, respectively, and the dimensionless parameters γ_a and γ_b and normalized current $\tilde{I}$ have been introduced. These quantities are given by:

(32) $\gamma_a=\frac{1}{4}a(b-a)\omega\mu_2\sigma_1$; $\gamma_b=\frac{1}{2}(c^2-b^2)(b-a)\omega\mu_2\sigma_3/b$; and

(33) $\tilde{I}=\frac{1}{2}(b-a)\omega\mu_2 I/(2\pi b)$.

EQN. 32 can be expressed in terms of dimensionless parameters by using EQN. 29. The results are:

(34) $\gamma_a=2(\sigma_1/\sigma_2)a\alpha_R{}^2/(b-a)$; $\gamma_b=4(\sigma_3/\sigma_2)(c^2-b^2)\alpha_R{}^2/\{b(b-a)\}$.

An alternative way of writing EQN. 34 is:

(35) $\gamma_a=(\sigma_1/\sigma_2)a\alpha_R/\delta$; $\gamma_b=2(\sigma_3/\sigma_2)(c^2-b^2)\alpha_R/(\delta b)$.

The mean power per unit length generated in the material is given by:

(36) $$P=\frac{1}{2}\left\{\sigma_1\pi a^2|E_a|^2+2\pi\sigma_2\int_a^b dr r|E_{S2}(r)|^2+\sigma_3\pi(c^2-b^2)|E_b|^2\right\}$$

$$=\frac{1}{2}\left\{\sigma_1\pi a^2|E_a|^2+\frac{1}{2}\pi(b^2-a^2)\sigma_2\int_{-1}^{1}d\chi\{1+\beta\chi\}|E_{S2}(r)|^2+\sigma_3\pi(c^2-b^2)|E_b|^2\right\}.$$

The AC resistance is then:

(37) $R_{AC}=P/(\frac{1}{2}|I|^2)$.

To obtain an approximate solution of EQN. 25, β is assumed to be small enough to be neglected in EQN. 25. This assumption holds if the thickness of the ferromagnetic material (material 2) is much less than its mean radius. The general solution then takes the form:

(38) $E_{S2}=Ae^{\alpha\chi}+Be^{-\alpha\chi}$.

Then:

(39) $E_a=Ae^{-\alpha}+Be^{\alpha}$; and

(40) $E_b=Ae^{\alpha}+Be^{-\alpha}$.

Substituting EQNS. 38-40 into EQNS. 30 and 31 yields the following set of equations for A and B:

(41) $\alpha(Ae^{-\alpha} - Be^{\alpha}) = -j\gamma_a(Ae^{-\alpha} + Be^{\alpha})$; and

(42) $\alpha(Ae^{\alpha} - Be^{-\alpha}) = j\gamma_b(Ae^{\alpha} + Be^{-\alpha}) - j\tilde{I}$.

Rearranging EQN. 41 obtains an expression for B in terms of A:

(43) $B = \dfrac{\alpha + j\gamma_a}{\alpha - j\gamma_a} e^{-2\alpha} A$.

This may be written as:

(44) $B = \dfrac{\alpha_R - i\gamma_a^{+}}{\alpha_R + i\gamma_a^{-}} e^{-2\alpha_R + 2i\alpha_R} A$,

with

(45) $\gamma_a^{\pm} = \gamma_a \pm \alpha_R$.

If

(46) $A = |A| \exp(i\phi_A)$

and everything is referred back to the phase of A, then:

(47) $\phi_A = 0$.

From EQN. 44:

(48) $B = |B| \exp(i\phi_B)$, with

(49) $|B| = (\Gamma_+ / \Gamma_-) \exp(-2\alpha_R) |A|$; and

(50) $\phi_B = 2\alpha_R - \phi_+ - \phi_-$; where

(51) $\Gamma_{\pm} = \left\{\alpha_R^{\,2} + (\gamma_a^{\pm})^2\right\}^{0.5}$; and

(52) $\phi_{\pm} = \tan^{-1}\{\phi_{\pm} / \alpha_R\}$.

Then:

(53) $E_a = |A| \exp(-\alpha_R + i\alpha_R) + |B| \exp\{\alpha_R + i(\phi_B - \alpha_R)\}$; and

(54) $E_b = |A| \exp(\alpha_R - i\alpha_R) + |B| \exp\{-\alpha_R + i(\phi_B + \alpha_R)\}$.

Hence:

(55A) $\mathrm{Re}[E_a] = |A| \exp(-\alpha_R)\cos(\alpha_R) + |B| \exp(\alpha_R)\cos(\phi_B - \alpha_R)$;

(55B) $\mathrm{Im}[E_a] = |A| \exp(-\alpha_R)\sin(\alpha_R) + |B| \exp(\alpha_R)\sin(\phi_B - \alpha_R)$;

(55C) $\mathrm{Re}[E_b] = |A| \exp(\alpha_R)\cos(\alpha_R) + |B| \exp(-\alpha_R)\cos(\phi_B + \alpha_R)$; and

(55D) $\mathrm{Im}[E_a] = -|A| \exp(\alpha_R)\sin(\alpha_R) + |B| \exp(-\alpha_R)\sin(\phi_B + \alpha_R)$.

The ratio of absolute values of currents flowing through the center and outer conductors is then given by:

(56) $\dfrac{|I_1|}{|I_3|} = \dfrac{a^2\sigma_1}{(c^2 - b^2)\sigma_3} \sqrt{\dfrac{\mathrm{Re}^2[E_a] + \mathrm{Im}^2[E_a]}{\mathrm{Re}^2[E_b] + \mathrm{Im}^2[E_b]}}$.

The total current flowing through the center conductor is given by:

(57) $I_2 = \sigma_2\pi(b^2 - a^2)(A + B)\sinh(\alpha)/\alpha$.

Now:

(58) $\sinh(\alpha)/\alpha = (1+i)\{\sinh(\alpha_R)\cos(\alpha_R) - i\cosh(\alpha_R)\sin(\alpha_R)\}/(2\alpha_R) = (S^{+} + S^{-}i)$, with

(59) $S^{\pm} = \{\sinh(\alpha_R)\cos(\alpha_R) \pm \cosh(\alpha_R)\sin(\alpha_R)\}/(4\alpha_R)$.

Hence:

(60) $\mathrm{Re}[I_2] = \sigma_2\pi(b^2 - a^2)\{\{|A| + |B|\cos(\phi_B)\}S^{+} - |B|\sin(\phi_B)S^{-}\}$; and

(61) $\mathrm{Im}[I_2] = \sigma_2\pi(b^2 - a^2)\{\{|A| + |B|\cos(\phi_B)\}S^{-} + |B|\sin(\phi_B)S^{+}\}$.

Root-mean-square current is therefore given by:

(62) $I_{rms}{}^2 = \tfrac{1}{2}\{(\mathrm{Re}[I_1] + \mathrm{Re}[I_2] + \mathrm{Re}[I_3])^2 + (\mathrm{Im}[I_1] + \mathrm{Im}[I_2] + \mathrm{Im}[I_3])^2\}$.

Furthermore, EQNS. 40-42 are used to evaluate the second term on the right-hand side of EQN. 29 (neglecting the term in β). The result is:

(63) $P = \tfrac{1}{2}\{\sigma_1\pi a^2 |E_a|^2 + \pi(c^2 - b^2)\sigma_3 |E_b|^2$
$+ \pi(b^2 - a^2)\sigma_2[(|A|^2 + |B^2|)\sinh(2\alpha_R)/(2\alpha_R) + 2|A||B|\sin(\phi_B + 2\alpha_R)/(\phi_B + 2\alpha_R)]\}$.

Dividing EQN. 63 by EQN. 62 yields an expression for the AC resistance (cf. EQN. 37).

Given values for the dimensions a, b and c, and σ_1, σ_2 and σ_3, which are known functions of temperature, and assuming a value for the relative magnetic permeability of the ferromagnetic material (material 2), or equivalently, the skin depth δ, $A = 1$ can be set and the AC resistance per unit length R_{AC} can be calculated. The ratio of the root-mean square current flowing through the inner conductor (material 1) and the ferromagnetic material (material 2) to the total can also be calculated. For a given total RMS current, then, the RMS current flowing through materials 1 and 2 can be calculated, which gives the magnetic field at the surface of material 2. Using magnetic data for material 2, a value for μ_2/μ_0 can be deduced and hence a value for δ can be deduced. Plotting this skin depth against the original skin depth produces a pair of curves that cross at the true δ.

Magnetic data was obtained for carbon steel as a ferromagnetic material. B versus H curves, and hence relative permeabilities, were obtained from the magnetic data at various temperatures up to 1100 °F and magnetic fields up to 200 Oe (oersteds). A correlation was found that fitted the data well through the maximum permeability and beyond. FIG. 14 depicts examples of relative magnetic permeability (y-axis) versus magnetic field (Oe) for both the found correlations and raw data for carbon steel. Data 274 is raw data for carbon steel at 400 °F. Data 276 is raw data for carbon steel at 1000 °F. Curve 278 is the found correlation for carbon steel at 400 °F. Curve 280 is the found correlation for carbon steel at 1000 °F.

For the dimensions and materials of the copper/carbon steel/347H heater element in the experiments above, the theoretical calculations described above were carried out to calculate magnetic field at the outer surface of the carbon steel as a function of skin depth. Results of the theoretical calculations were presented on the same plot as skin depth versus magnetic field from the correlations applied to the magnetic data from FIG. 14. The theoretical calculations and correlations were made for four temperatures (200 °F, 500 °F, 800 °F, and 1100 °F) and five total root-mean-square (RMS) currents (100 A, 200 A, 300 A, 400 A, and 500 A).

FIG. 15 shows the resulting plots of skin depth (in) versus magnetic field (Oe) for all four temperatures and 400 A current. Curve 282 is the correlation from magnetic data at 200 °F. Curve 284 is the correlation from magnetic data at 500 °F. Curve 286 is the correlation from magnetic data at 800 °F. Curve 288 is the correlation from magnetic data at 1100 °F. Curve 290 is the theoretical calculation at the outer surface of the carbon steel as a function of skin depth at 200 °F. Curve 292 is the theoretical calculation at the outer surface of the carbon steel as a function of skin depth at 500 °F. Curve 294 is the theoretical calculation at the outer surface of the carbon steel as a function of skin depth at 800 °F. Curve 296 is the theoretical calculation at the outer surface of the carbon steel as a function of skin depth at 1100 °F.

The skin depths obtained from the intersections of the same temperature curves in FIG. 15 were input into the equations described above and the AC resistance per unit length was calculated. The total AC resistance of the entire heater, including that of the canister, was subsequently calculated. A comparison between the experimental and numerical (calculated) results is shown in FIG. 16 for currents of 300 A (experimental data 298 and numerical curve 300), 400A (experimental data 302 and numerical curve 304), and 500 A (experimental data 306 and numerical curve 308). Though the numerical results exhibit a steeper trend than the experimental results, the theoretical model captures the close bunching of the experimental data, and the overall values are quite reasonable given the assumptions involved in the theoretical model. For example, one assumption involved the use of a permeability derived from a quasistatic B-H curve to treat a dynamic system.

One feature of the theoretical model describing the flow of alternating current in the three-part temperature limited heater is that the AC resistance does not fall off monotonically with increasing skin depth. FIG. 17 shows the AC resistance (mΩ) per foot of the heater element as a function of skin depth (in.) at 1100 °F calculated from the theoretical model. The AC resistance may be maximized by selecting the skin depth that is at the peak of the non-monotonical portion of the resistance versus skin depth profile (for example, at about 0.23 in. in FIG. 17).

FIG. 18 shows the power generated per unit length (W/ft) in each heater component (curve 310 (copper core), curve 312 (carbon steel), curve 314 (347H outer layer), and curve 316 (total)) versus skin depth (in.). As expected, the power dissipation in the 347H falls off while the power dissipation in the copper core increases as the skin depth increases. The maximum power dissipation in the carbon steel occurs at the skin depth of about 0.23 inches and is expected to correspond to the minimum in the power factor, as shown in FIG. 12. The current density in the carbon steel behaves like a damped wave of wavelength $\lambda = 2\pi\delta$ and the effect of this wavelength on the boundary conditions at the copper/carbon steel and carbon steel/347H interface may be behind the structure in FIG. 17. For example, the local minimum in AC resistance is close to the value at which the thickness of the carbon steel layer corresponds to $\lambda/4$.

Formulae may be developed that describe the shapes of the AC resistance versus temperature profiles of temperature limited heaters for use in simulating the performance of the heaters in a particular embodiment. The data in FIGS. 10 and 11 show that the resistances initially rise linearly, then drop off increasingly steeply towards the DC lines. The resistance versus temperature profile of each heater can be described by:

(64) $R_{AC} = A_{AC} + B_{AC}T$; $T << T_C$; and

(65) $R_{AC} = R_{DC} = A_{DC} + B_{DC}T$; $T >> T_C$.

Note that A_{DC} and B_{DC} are independent of current, while A_{AC} and B_{AC} depend on the current. Choosing as a form crossing over between EQNS. 64 and 65 results in the following expression for R_{AC}:

(66)

$R_{AC} = \frac{1}{2}\{1 + \tanh\{\alpha(T_0 - T)\}\}\{A_{AC} + B_{AC}T\} + \frac{1}{2}\{1 - \tanh\{\alpha(T_0 - T)\}\}\{A_{DC} + B_{DC}T\}$ $T \leq T_0$; and

$R_{AC} = \frac{1}{2}\{1 + \tanh\{\beta(T_0 - T)\}\}\{A_{AC} + B_{AC}T\} + \frac{1}{2}\{1 - \tanh\{\beta(T_0 - T)\}\}\{A_{DC} + B_{DC}T\}$ $T \geq T_0$.

Since A_{AC} and B_{AC} are functions of current, then:

(67) $A_{AC} = A_{AC}^{(0)} + A_{AC}^{(1)}I; B_{AC} = B_{AC}^{(0)} + B_{AC}^{(1)}I$.

The parameter α is also a function of current, and exhibits the quadratic dependence:

$$(68)\quad \alpha = \alpha_0 + \alpha_1 I + \alpha_2 I^2 .$$

The parameters β, T_0, as well as A_{DC} and B_{DC} are independent of current. Values of the parameters for the copper/carbon steel/347H heaters in the above experiments are listed in TABLE 2.

TABLE 2

Parameter	Unit	copper/carbon steel/347H
A_{DC}	mΩ	0.6783
B_{DC}	mΩ/°F	6.53×10^{-4}
$A_{AC}^{(0)}$	mΩ	3.6358
$A_{AC}^{(1)}$	mΩ/A	-1.247×10^{-3}
$B_{AC}^{(0)}$	mΩ/°F	2.3575×10^{-3}
$B_{AC}^{(1)}$	mΩ/(°FA)	-2.28×10^{-7}
α_0	1/°F	0.2
α_1	1/(°FA)	-7.9×10^{-4}
α_2	1/(°FA^2)	8×10^{-7}
β	1/°F	0.017
T_0	°F	1350

FIGS. 19A-C compare the results of the theoretical calculations in EQNS. 66-68 with the experimental data at 300A (FIG. 19A), 400 A (FIG. 19B) and 500 A (FIG. 19C). FIG. 19A depicts electrical resistance (mΩ) versus temperature (°F) at 300 A. Data 318 is the experimental data at 300 A. Curve 320 is the theoretical calculation at 300 A. Curve 322 is a plot of resistance versus temperature at 10 A DC. FIG. 19B depicts electrical resistance (mΩ) versus temperature (°F) at 400 A. Data 324 is the experimental data at 400 A. Curve 326 is the theoretical calculation at 400 A. Curve 328 is a plot of resistance versus temperature at 10 A DC. FIG. 19C depicts electrical resistance (mΩ) versus temperature (°F) at 500 A. Data 330 is the experimental data at 500 A. Curve 332 is the theoretical calculation at 500 A. Curve 334 is a plot of resistance versus temperature at 10 A DC. Note that, to obtain the resistance per foot, for example, in simulation work, the resistances given by the theoretical calculations must be divided by six.

Further modifications and alternative embodiments of various aspects of the invention may be apparent to those skilled in the art in view of this description. Accordingly, this description is to be construed as illustrative only and is for the purpose of teaching those skilled in the art the general manner of carrying out the invention. It is to be understood that the forms of the invention shown and described herein are to be taken as the presently preferred embodiments. Elements and materials may be substituted for those illustrated and described herein, parts and processes may be reversed, and certain features of the invention may be utilized independently, all as would be apparent to one skilled in the art after having the benefit of this description of the invention. Changes may be made in the elements described herein without departing from the spirit and scope of the invention as described in the following claims. In addition, it is to be understood that features described herein independently may, in certain embodiments, be combined.

CLAIMS

1. A heater, comprising:

a ferromagnetic conductor; and

an electrical conductor electrically coupled to the ferromagnetic conductor, wherein the ferromagnetic conductor is positioned relative to the electrical conductor such that an electromagnetic field produced by time-varying current flow in the ferromagnetic conductor confines a majority of the flow of the electrical current to the electrical conductor at temperatures below or near a selected temperature.

2. The heater as claimed in claim 1, wherein the selected temperature is the Curie temperature of the ferromagnetic conductor.

3. The heater as claimed in any of claims 1 or 2, wherein the ferromagnetic conductor and the electrical conductor are electrically coupled such that a power factor of the heater remains above 0.85, above 0.9, or above 0.95 during use of the heater.

4. The heater as claimed in any of claims 1-3, wherein the electrical conductor at least partially surrounds the ferromagnetic conductor.

5. The heater as claimed in any of claims 1-4, wherein the heater further comprises an inner electrical conductor, the inner conductor at least partially surrounded by and electrically coupled to the ferromagnetic conductor.

6. The heater as claimed in claim 5, wherein the inner electrical conductor comprises a strength member that provides at least some mechanical strength to support the heater.

7. The heater as claimed in any of claims 5 or 6, wherein the inner electrical conductor comprises copper and/or copper with tungsten fiber.

8. The heater as claimed in any of claims 1-7, wherein the heater further comprises a sheath at least partially surrounding the electrical conductor, the sheath comprising a corrosion resistant material.

9. The heater as claimed in any of claims 1-8, wherein the heater further comprises an electrical insulator at least partially surrounding the electrical conductor.

10. The heater as claimed in claim 9, wherein the heater further comprises an electrically conductive sheath at least partially surrounding the electrical insulator, wherein the sheath is electrically insulated from the electrical conductor by the electrical insulator.

11. The heater as claimed in any of claims 1-10, wherein the heater has a turndown ratio of at least 1.1.

12. The heater as claimed in any of claims 1-11, wherein the electrical conductor provides a majority of a resistive heat output of the heater at temperatures up to approximately the selected temperature.

13. The heater as claimed in any of claims 1-12, wherein the ferromagnetic conductor and the electrical conductor are concentrically coupled.

14. The heater as claimed in any of claims 1-13, wherein the electrical conductor and the ferromagnetic conductor are longitudinally coupled.

15. The heater as claimed in any of claims 1-14, wherein the heater is configured to provide (a) a first heat output below the selected temperature, and (b) a second heat output approximately at and above the selected temperature, the second heat output being reduced compared to the first heat output.

16. The heater as claimed in claim 15, wherein the heater is configured to automatically provide the second heat output.

17. The heater as claimed in any claims 15 or 16, wherein the second heat output is at most 90% of the first heat output, the first heat output being at 50 °C below the selected temperature.

18. The heater as claimed in any of claims 1-17, wherein the heater is configured to allow heat to transfer from the heater to a part of a subsurface formation.

19. The heater as claimed in any of claims 1-18, wherein the heater is configured to be placed in an opening in a subsurface formation.

20. The heater as claimed in any of claims 1-19, wherein the ferromagnetic conductor is configured to substantially concentrate time-varying electrical current flow to the electrical conductor at temperatures below or near the selected temperature.

21. A method for controlling the heater in any of claims 1-20, the method comprising:

assessing an electrical characteristic of the heater in the subsurface formation, the heater being configured to heat at least a portion of the formation;

comparing the assessed electrical characteristic to predicted behavior for the electrical characteristic; and

controlling the heater based on the comparison.

22. The method as claimed in claim 21, wherein the electrical characteristic is the resistance of the heater.

23. The method as claimed in any of claims 21 or 22, wherein the electrical characteristic is a power factor of the heater.

24. The method as claimed in any of claims 21-23, wherein the method further comprises assessing the electrical characteristic based on electrical measurements of the heater.

25. The method as claimed in any of claims 21-24, wherein the method further comprises assessing the predicted behavior for the electrical characteristic using experimental measurements, analytical equations, and/or simulations.

26. The method as claimed in any of claims 21-25, wherein the predicted behavior for the electrical characteristic is assessed as a function of temperature of the heater.

27. The method as claimed in any of claims 21-26, wherein comparing the assessed electrical characteristic to the predicted behavior for the electrical characteristic assesses a temperature of the heater.

28. The method as claimed in any of claims 21-27, wherein controlling the heater comprises controlling the current and/or the power provided to the heater.

29. The method as claimed in any of claims 21-28, wherein the assessed electrical characteristic is the percentage of the heater length operating near or above the selected temperature of the heater.

30. A method of heating a subsurface formation using the heater in any of claims 1-19, the method comprising providing heat to a portion of the subsurface formation.

31. The method as claimed in claim 30, wherein the subsurface formation comprises hydrocarbons, the method further comprising allowing the heat to transfer to the formation such that at least some hydrocarbons are pyrolyzed in the formation.

32. The method as claimed in any of claims 30 or 31, further comprising producing a fluid from the formation.

33. A composition comprising hydrocarbons produced using the heater as claimed in any of claims 1-20, or using the method as claimed in any of claims 30-32.

34. A transportation fuel made from the composition as claimed in claim 33.

35. A heater, comprising:

a ferromagnetic conductor; and

an electrical conductor positioned relative to the ferromagnetic conductor such that an electromagnetic field produced by current flow in the ferromagnetic conductor confines at least a majority of the flow of the electrical current to the electrical conductor at temperatures below a selected temperature.

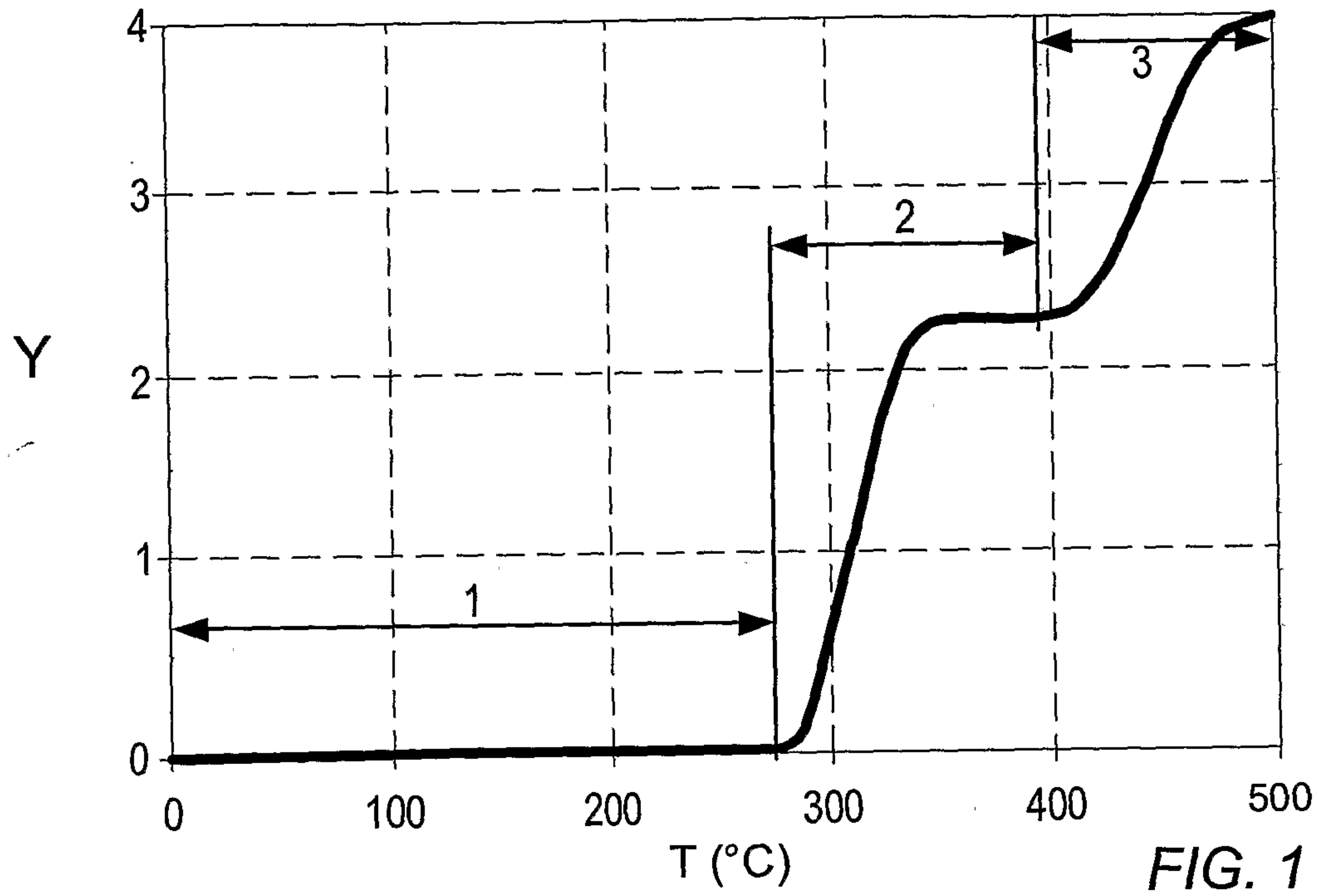
Y
4
3
2
1
0
0
100
200
300
400
500
T (°C)
1
2
3

FIG. 1

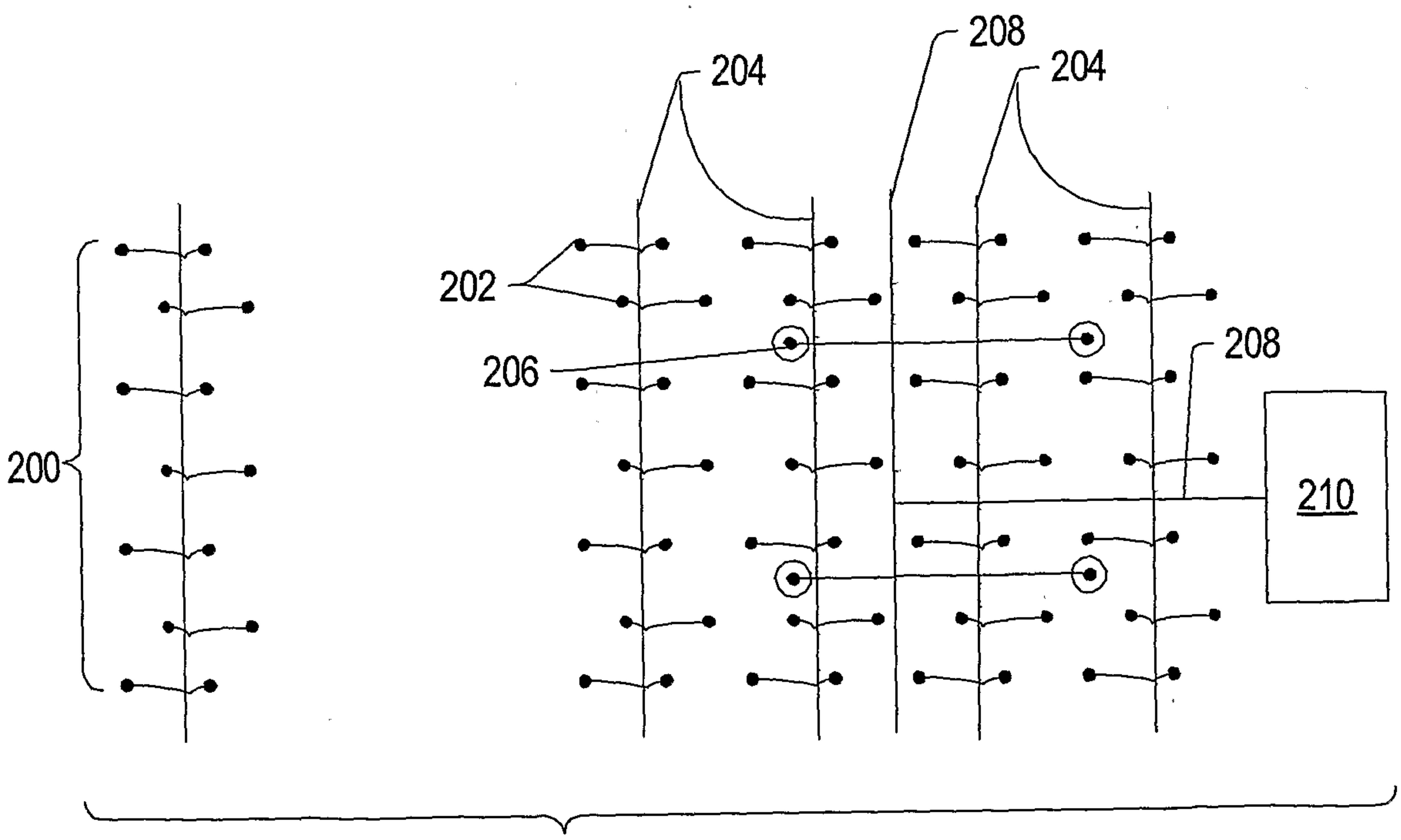
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FIG. 2

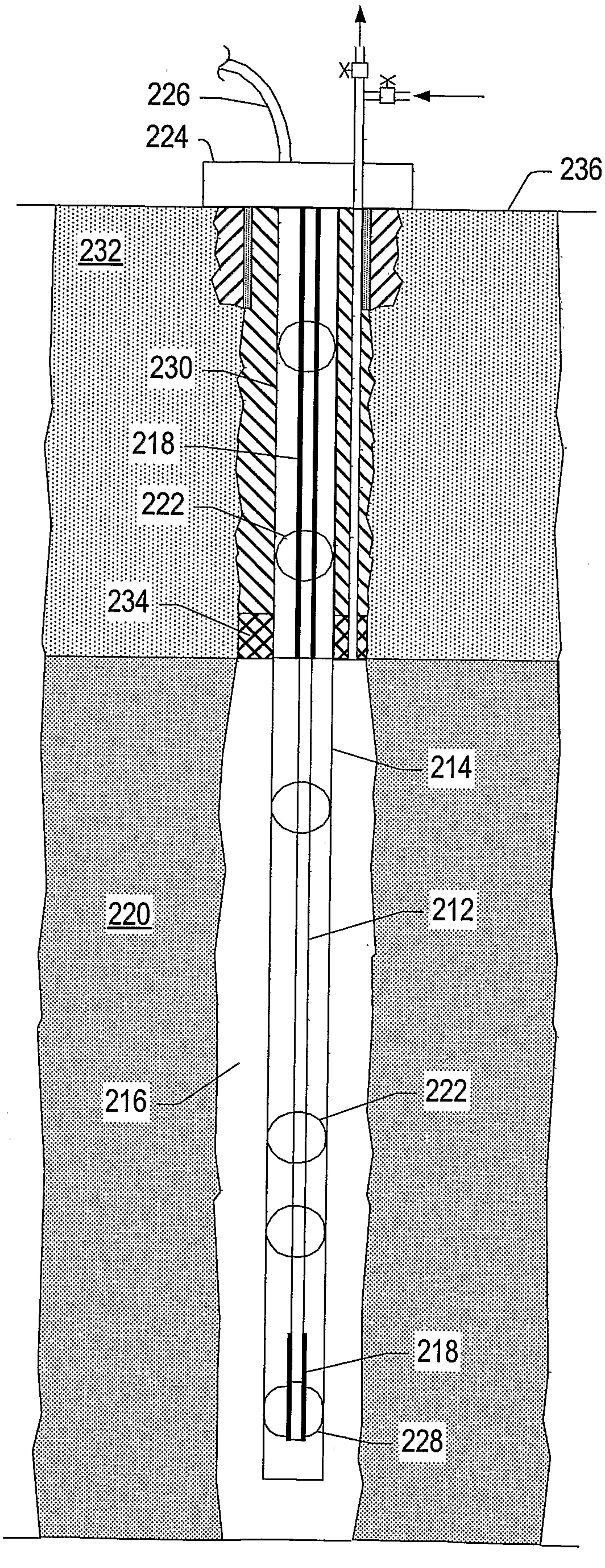


FIG. 3

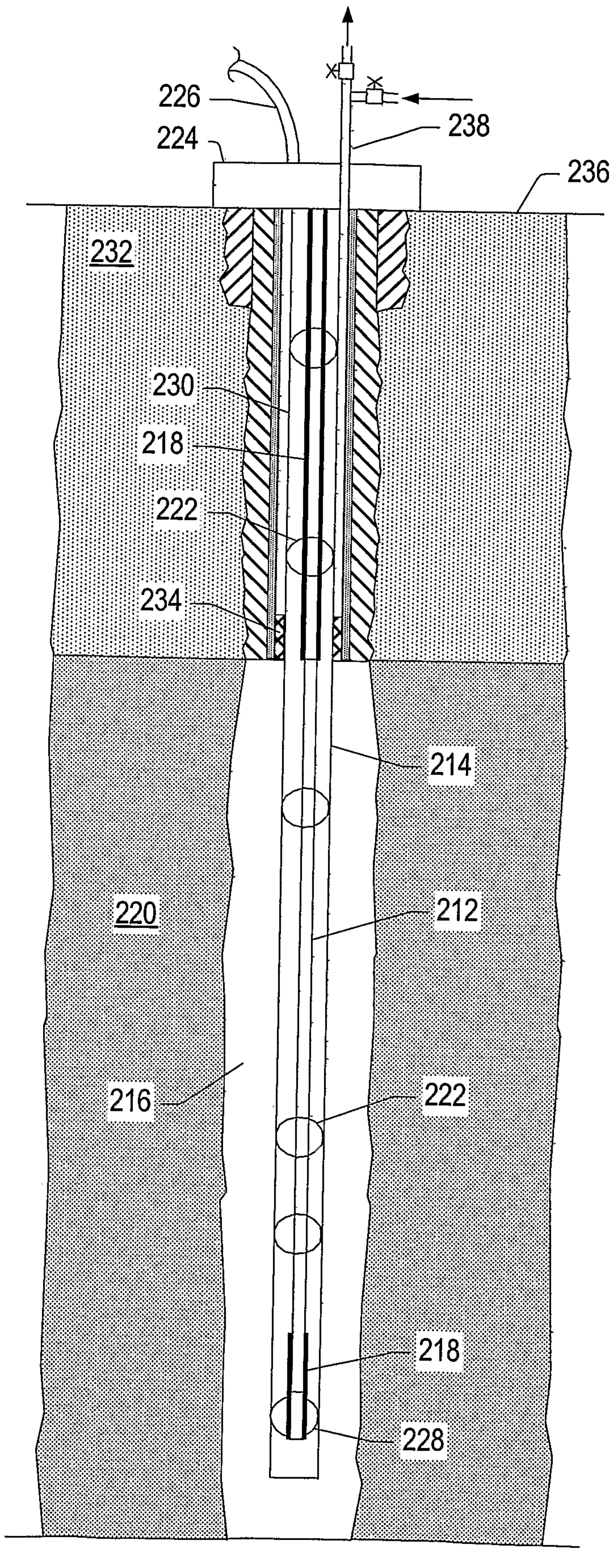


FIG. 4

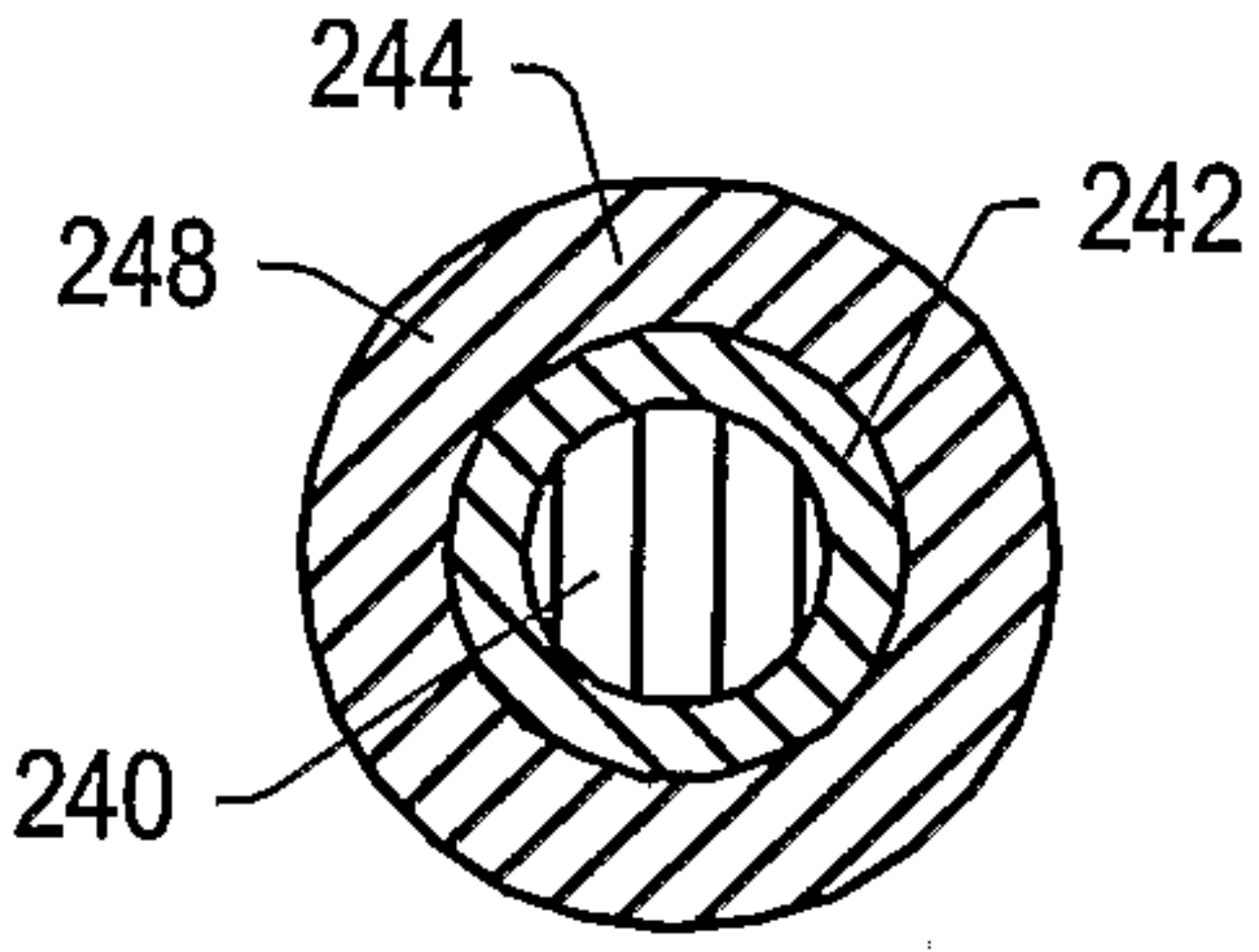


FIG. 5

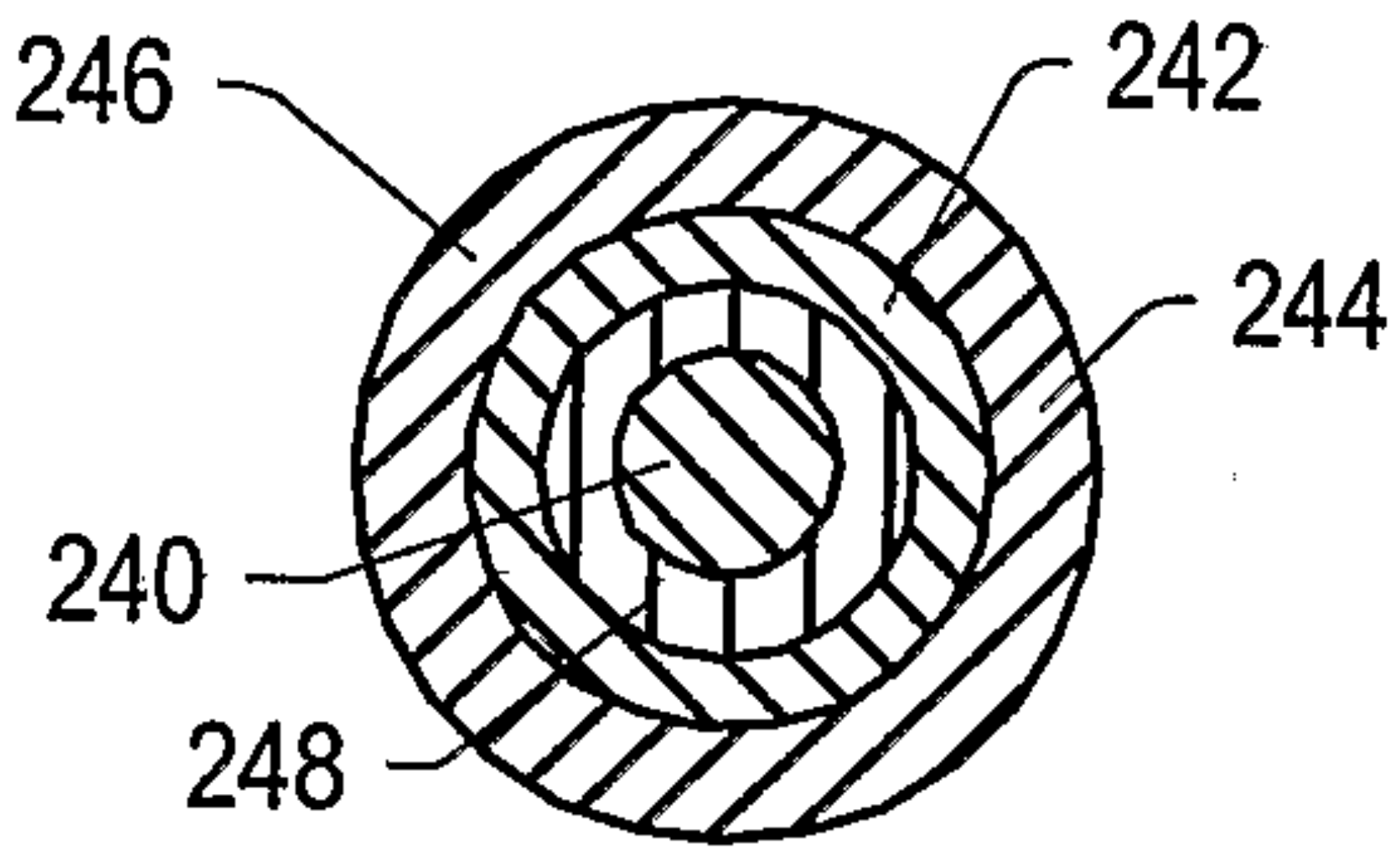


FIG. 6

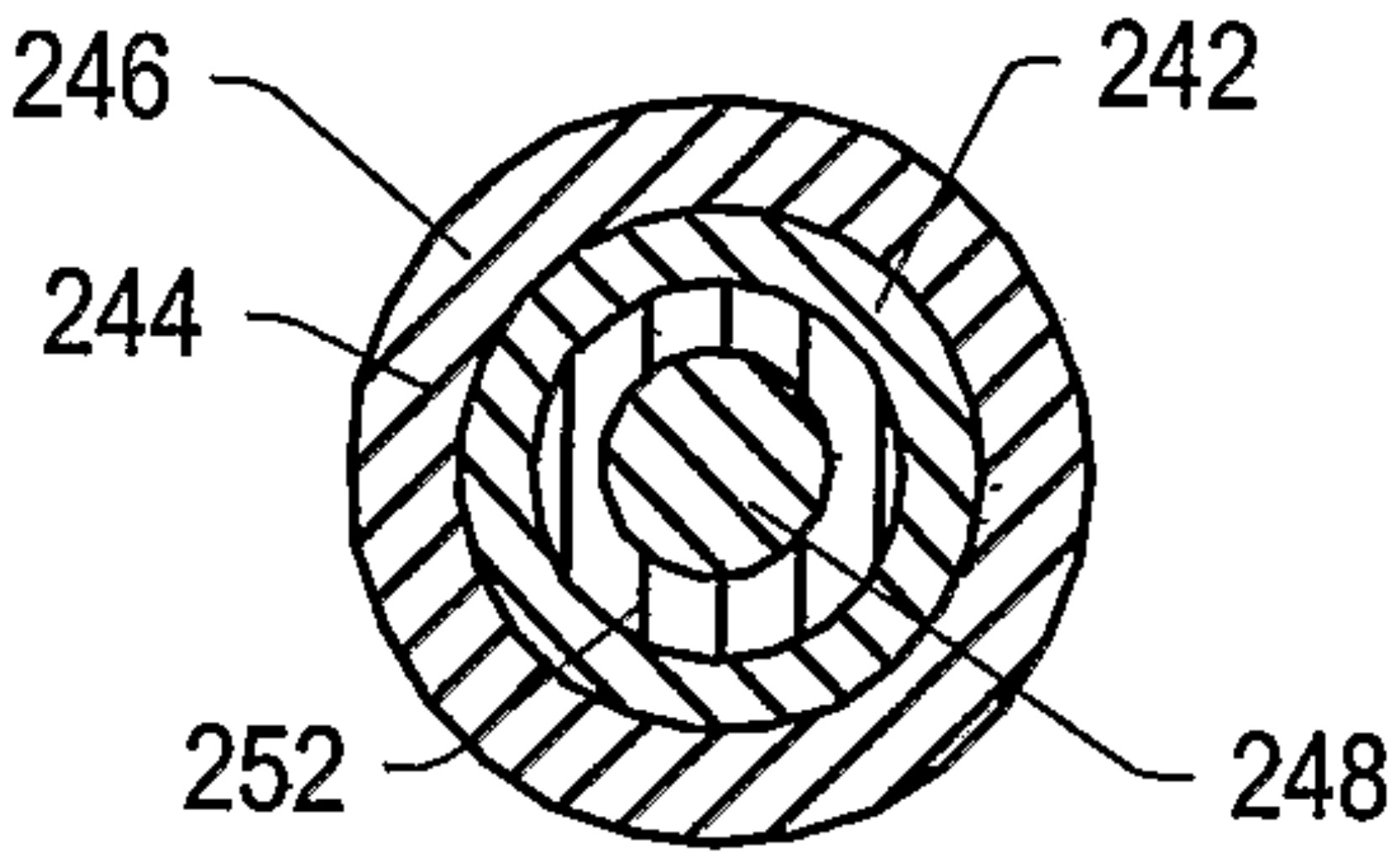


FIG. 7

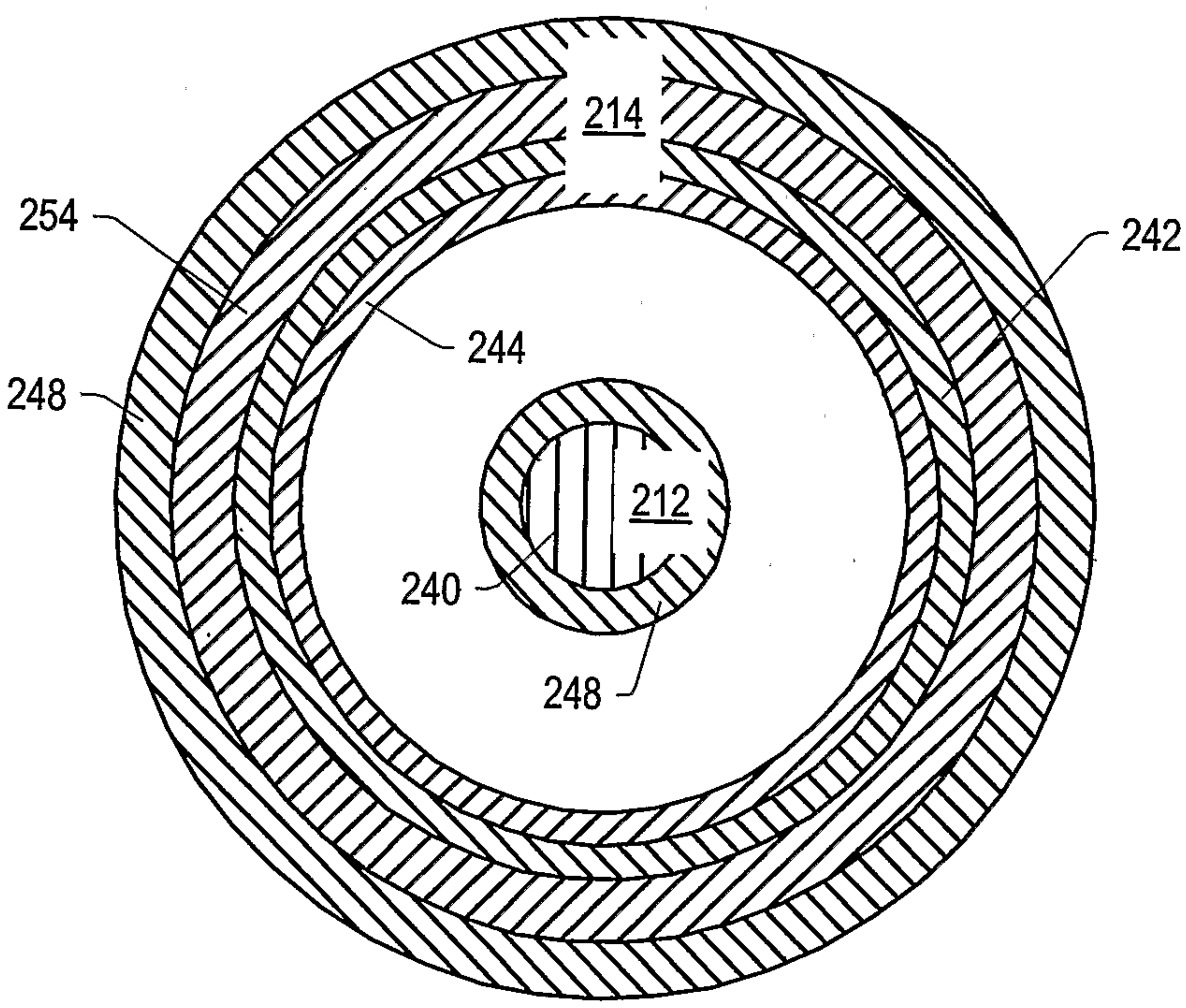


FIG. 9

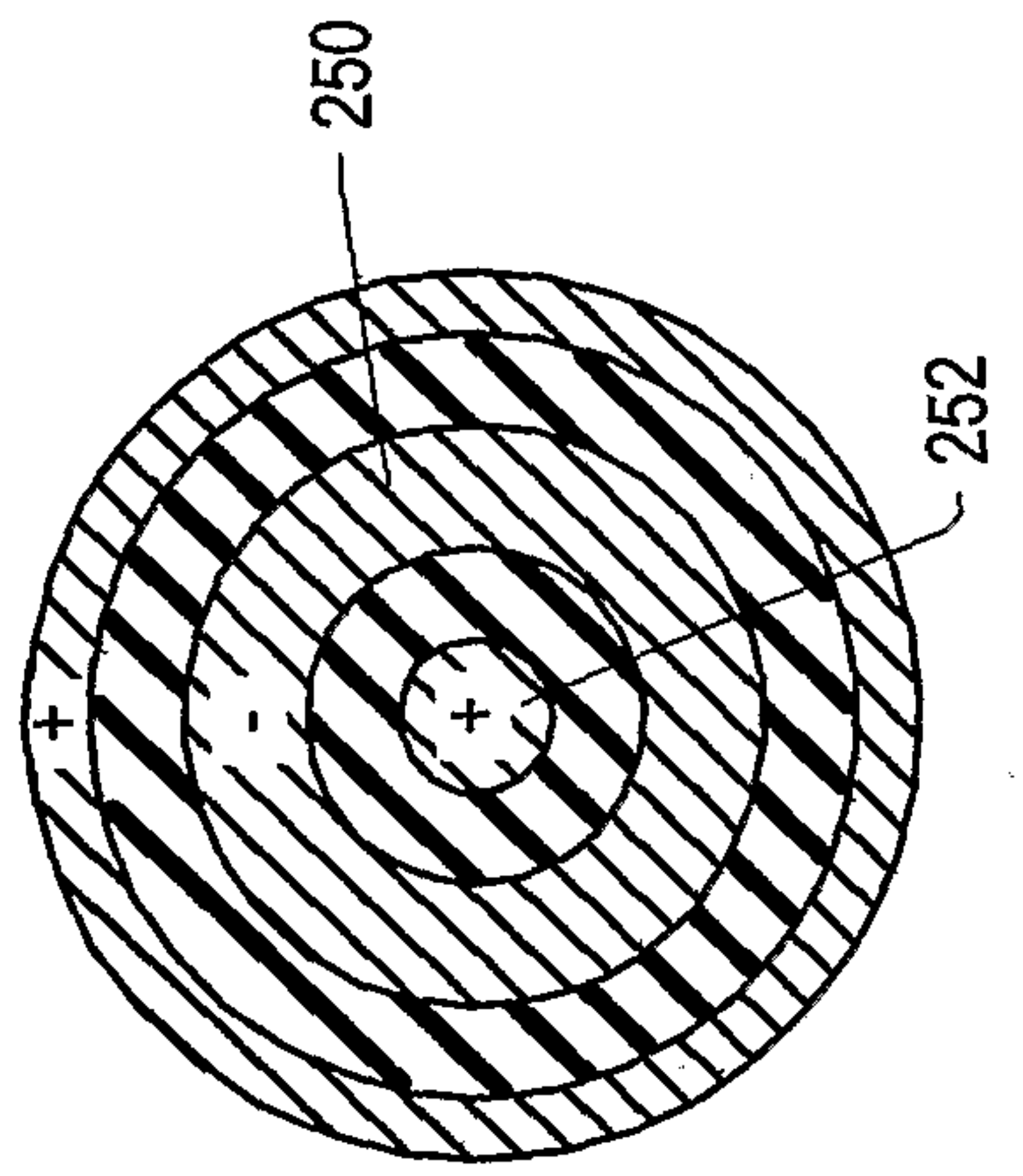


FIG. 8B

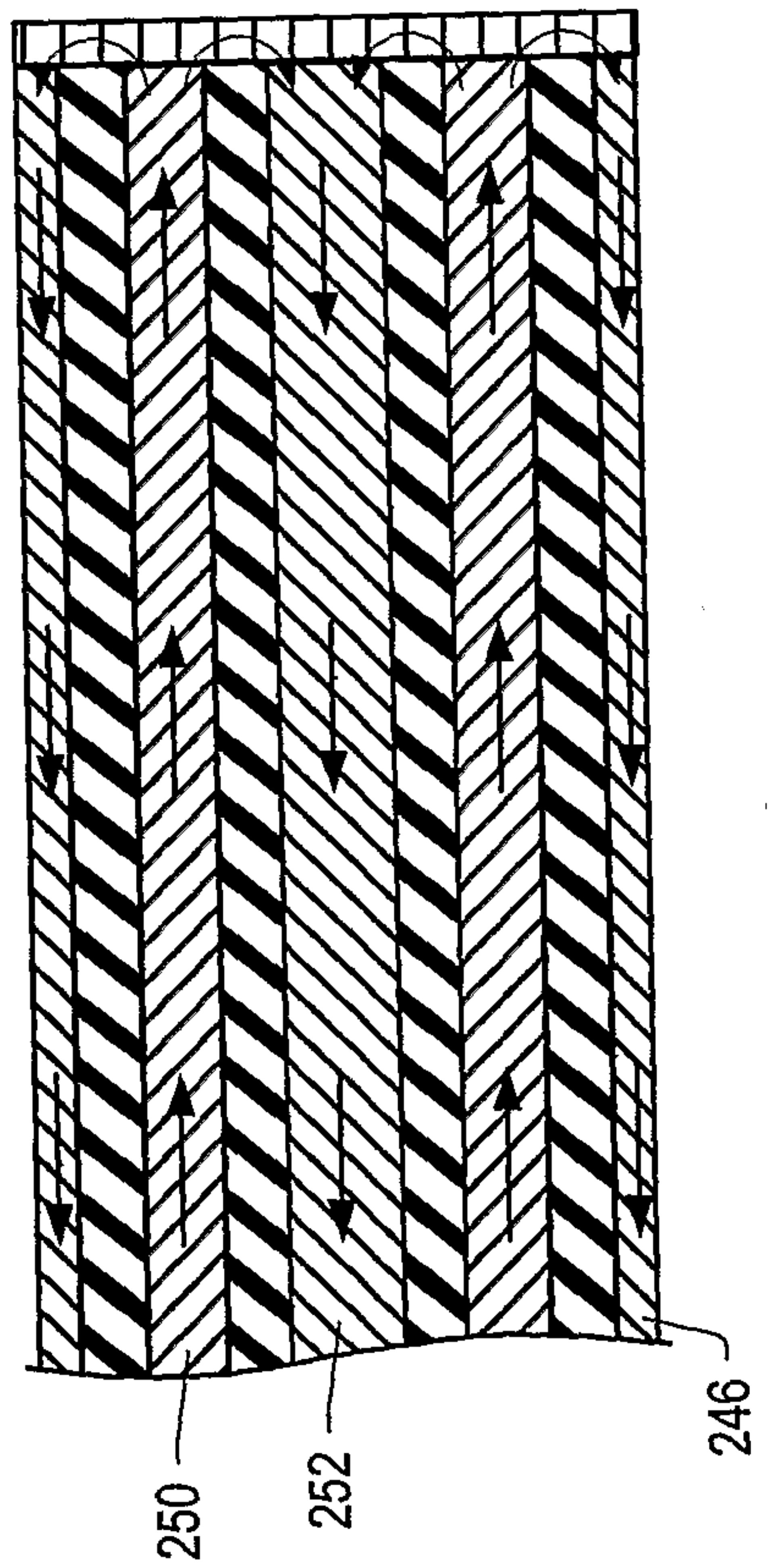
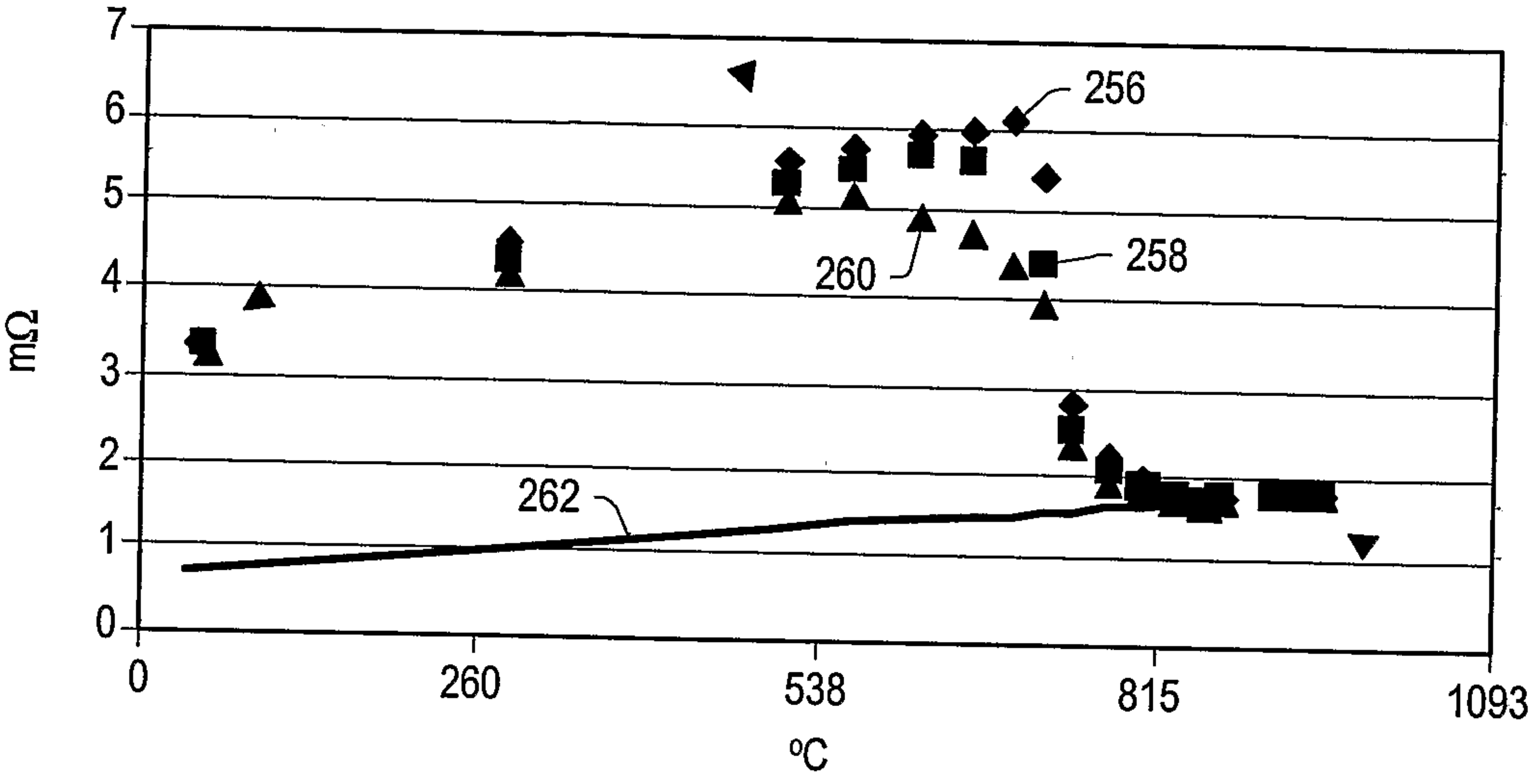


FIG. 8A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4
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mΩ
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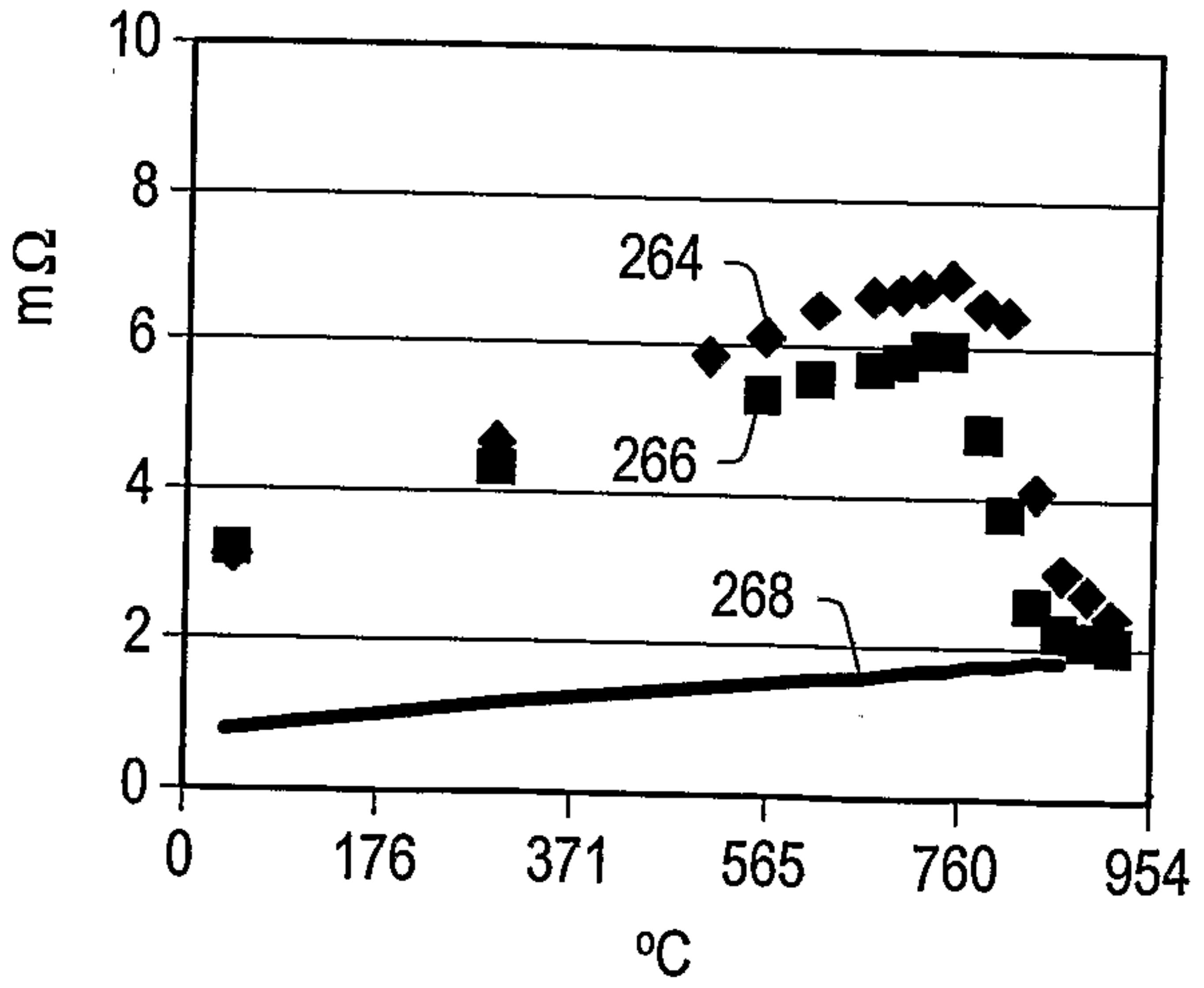
258
260
262
0
260
538
815
1093
°C

FIG. 10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mΩ
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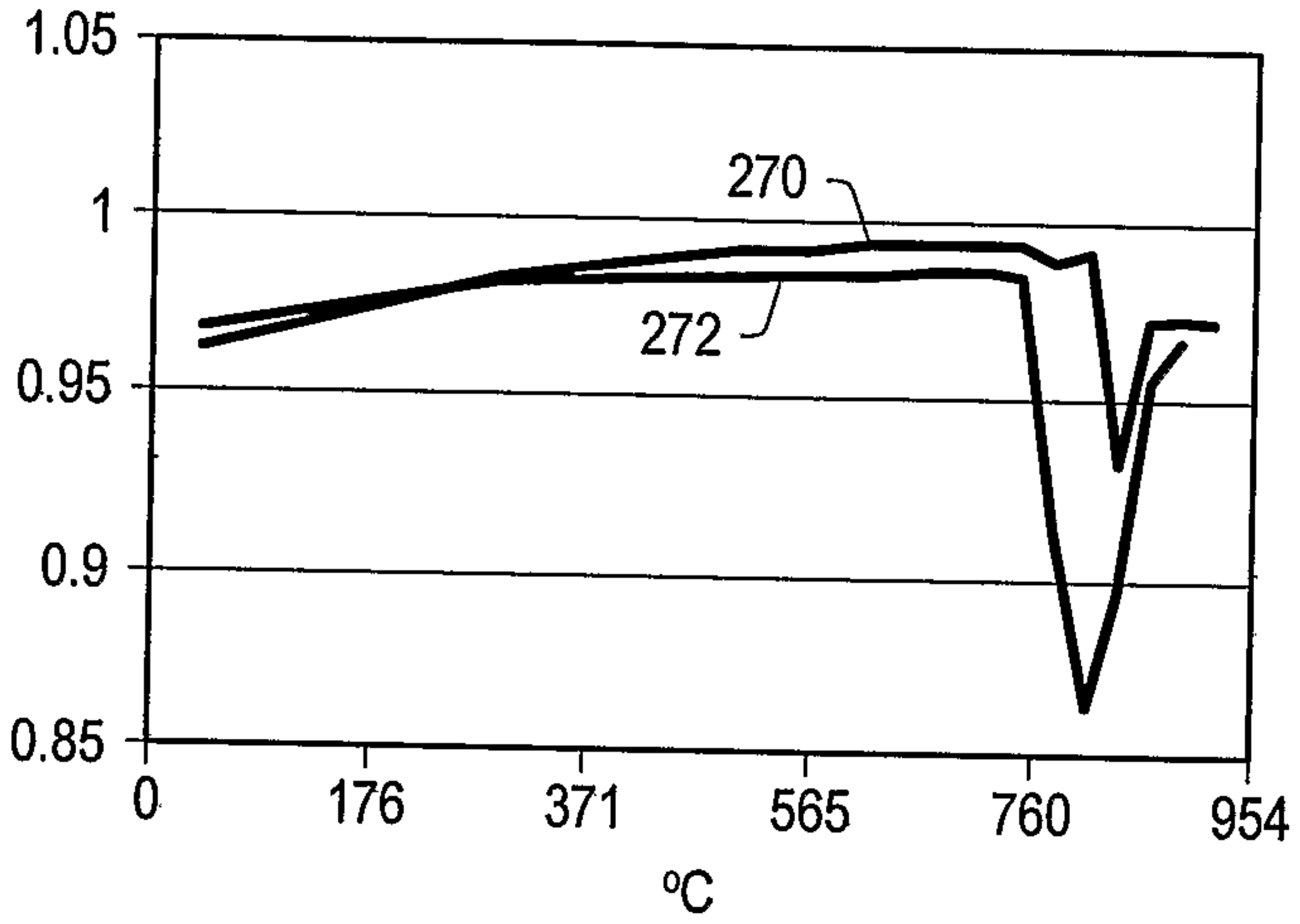
760
954
°C

FIG. 11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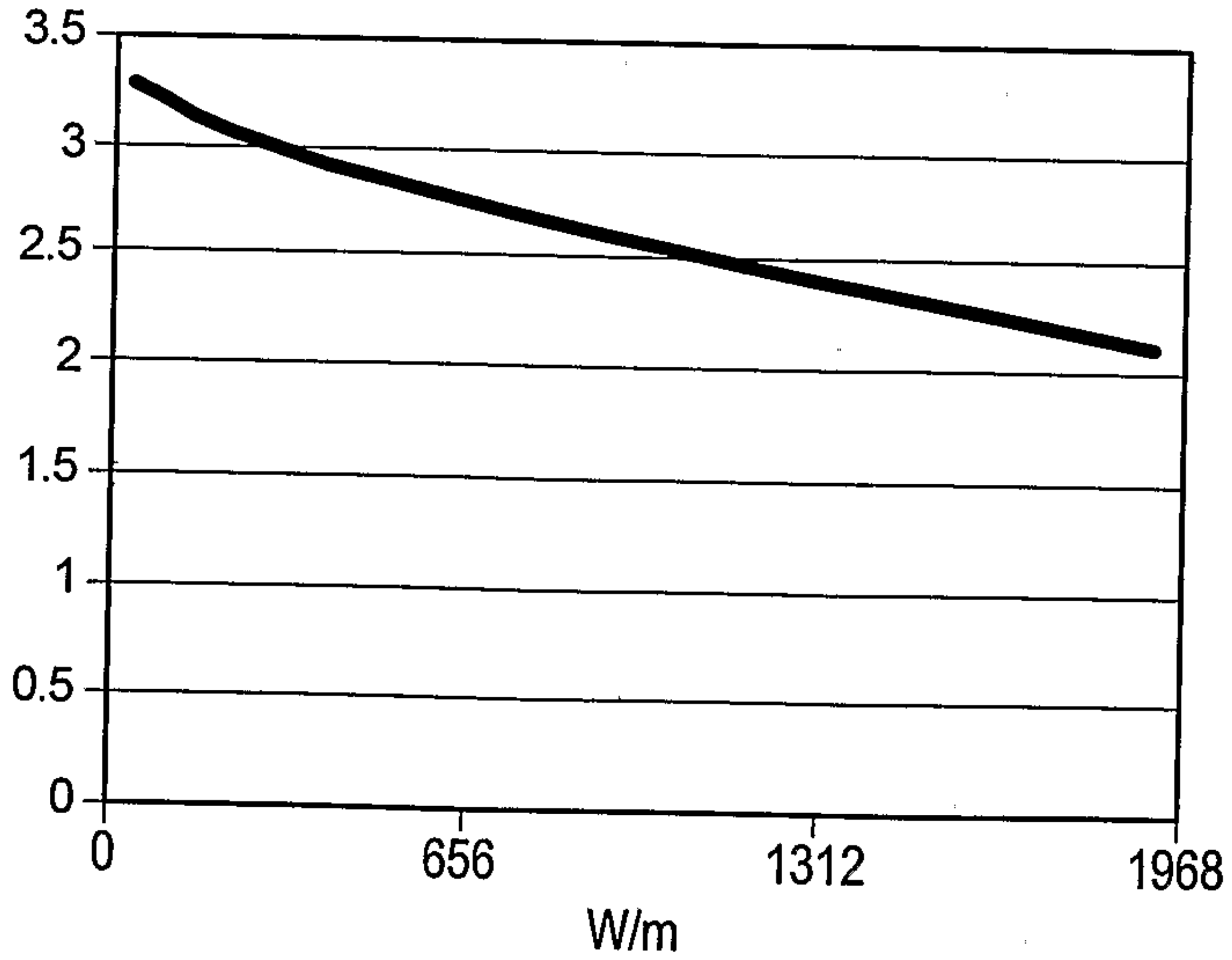
0.95
0.9
0.85
0
176
371
565
760
954
°C
270
272

FIG. 12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2.5
2
1.5
1
0.5
0
0
656
1312
1968
W/m

FIG. 13

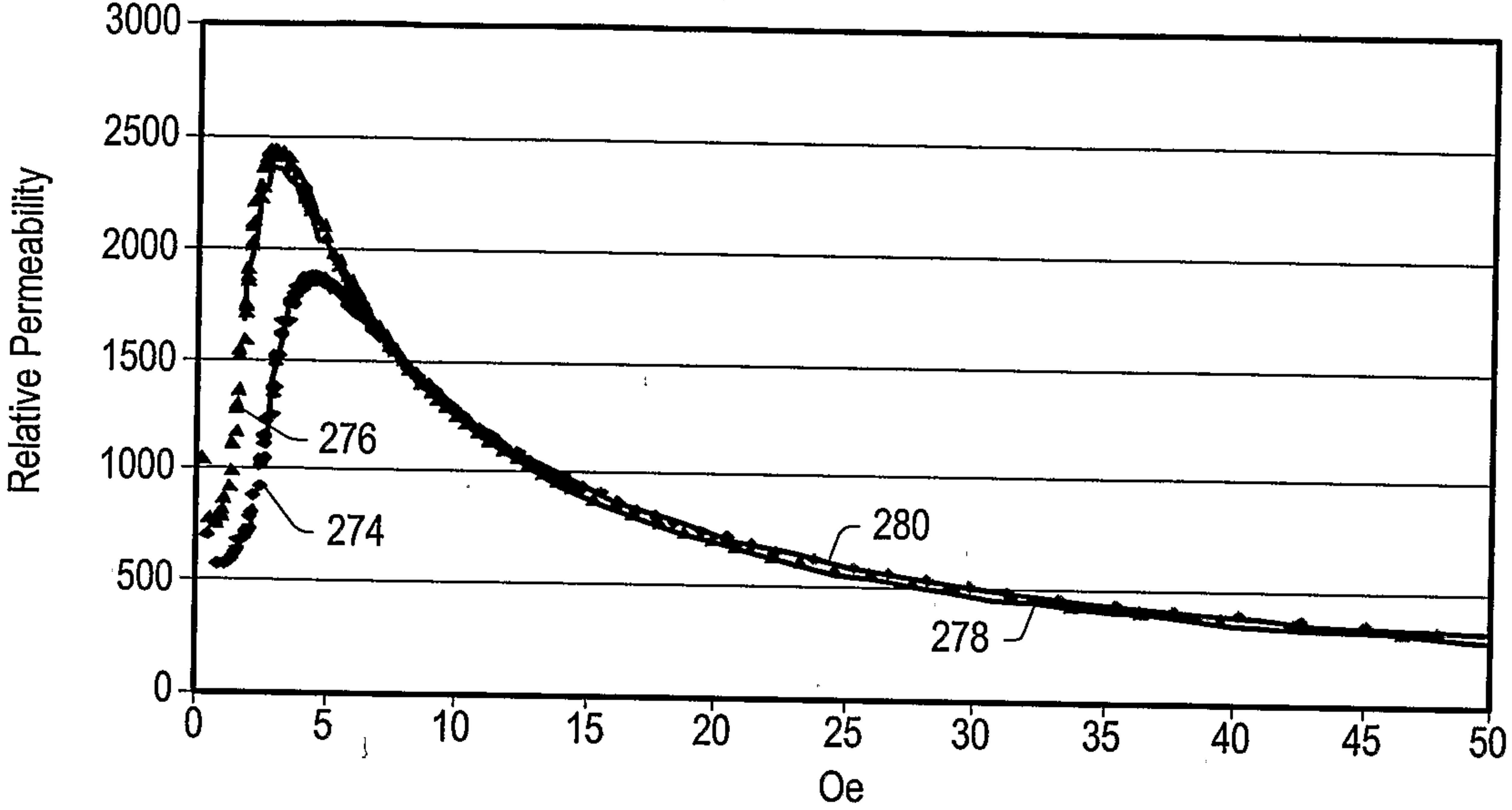


FIG. 14

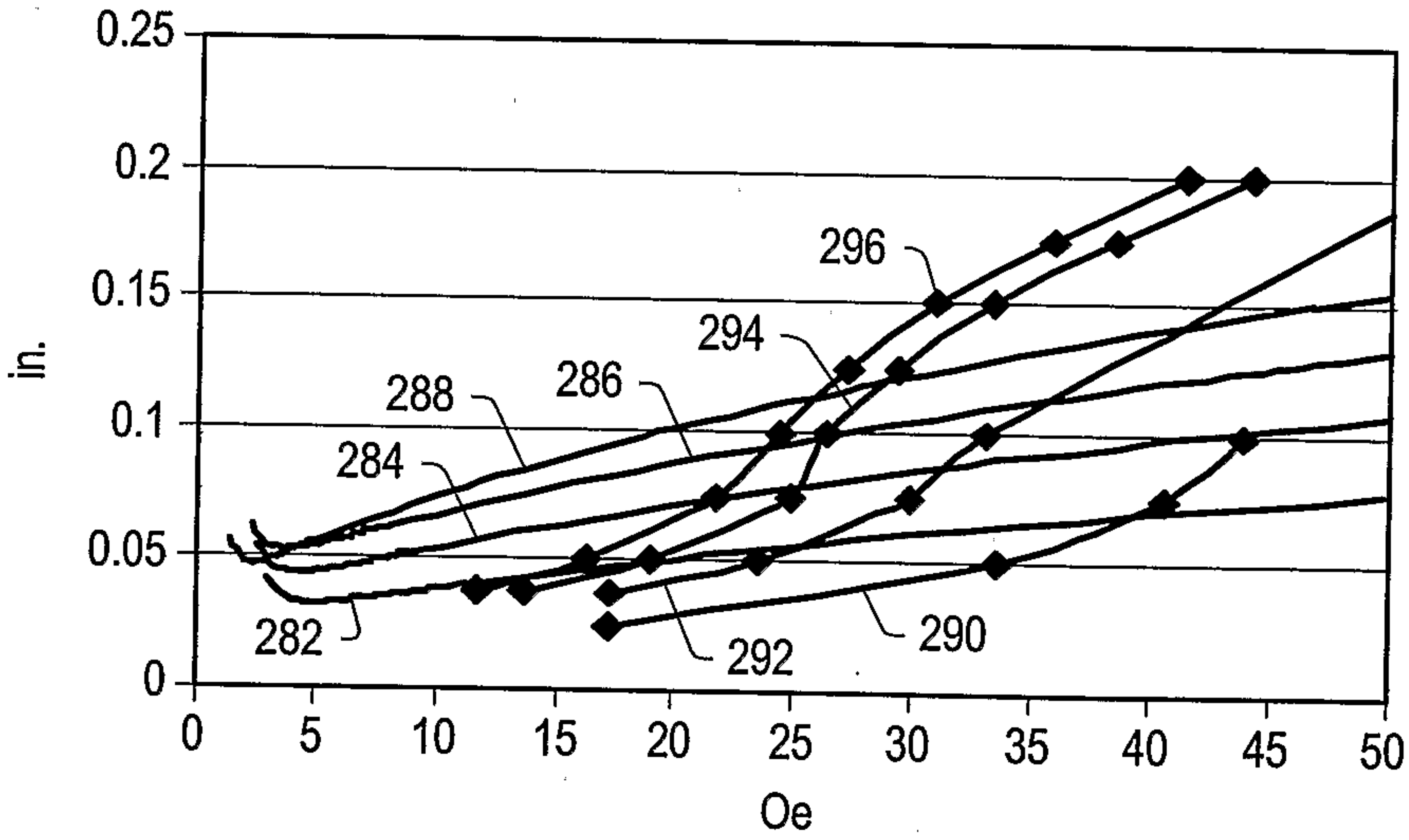


FIG. 15

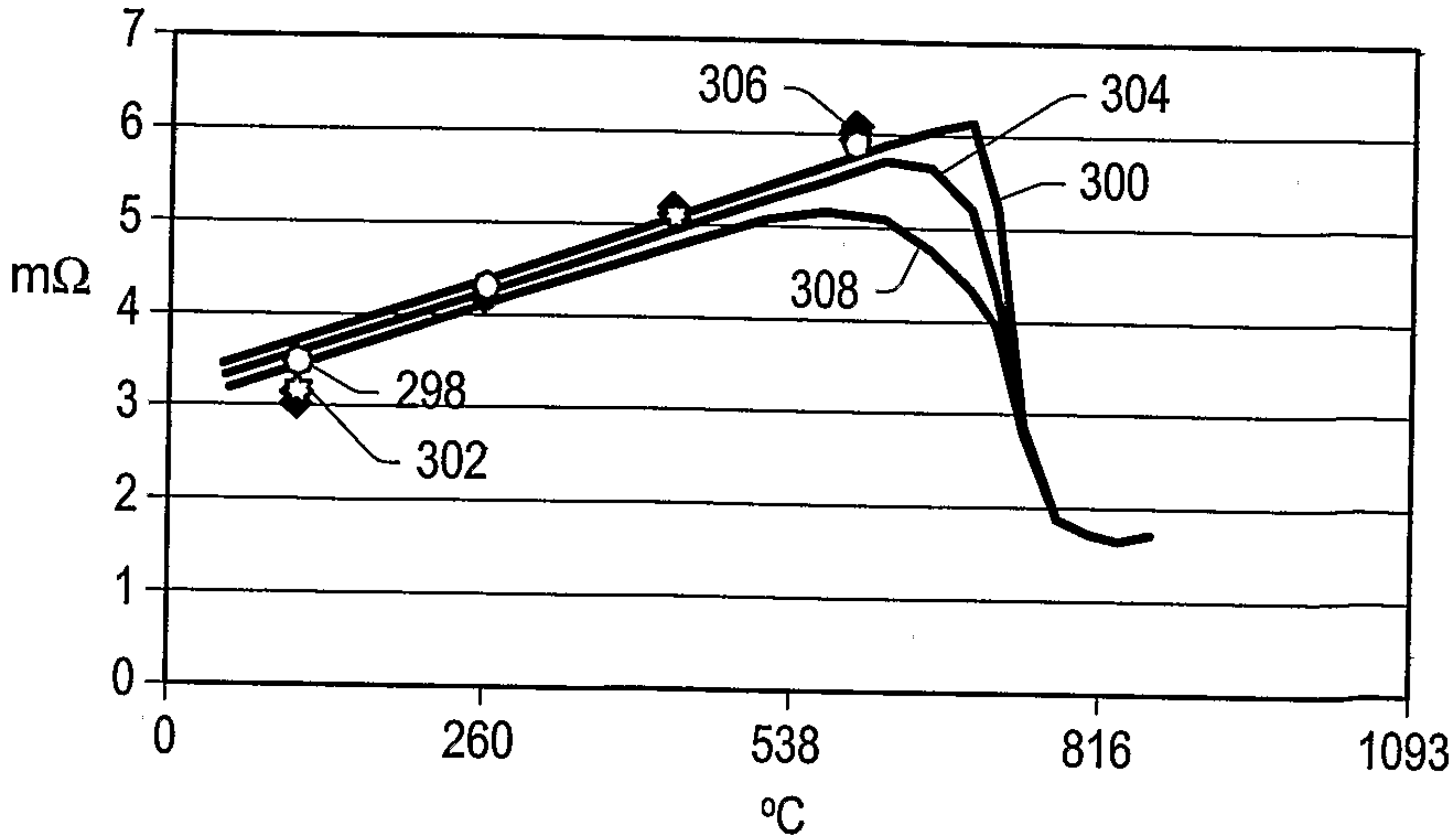
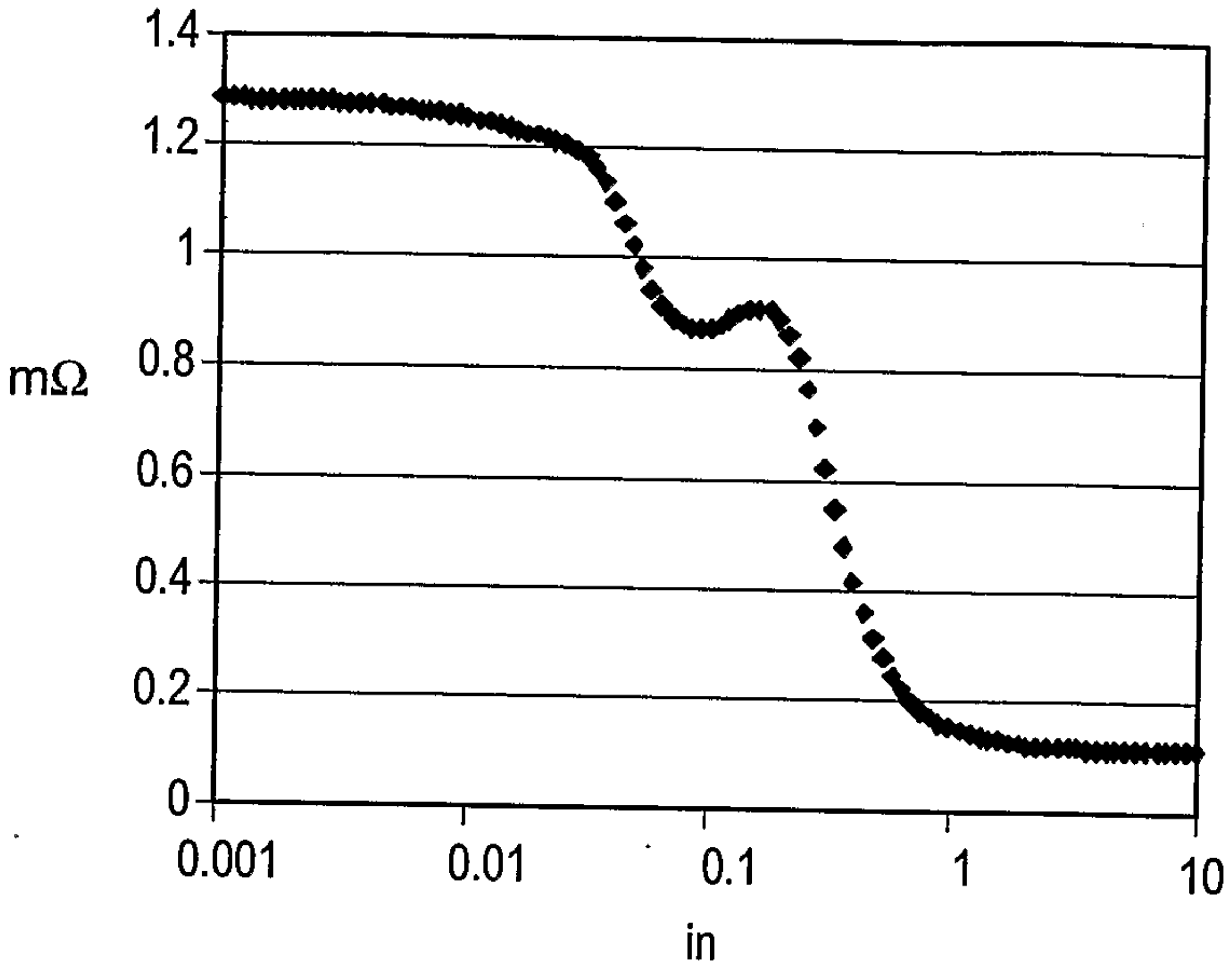


FIG. 16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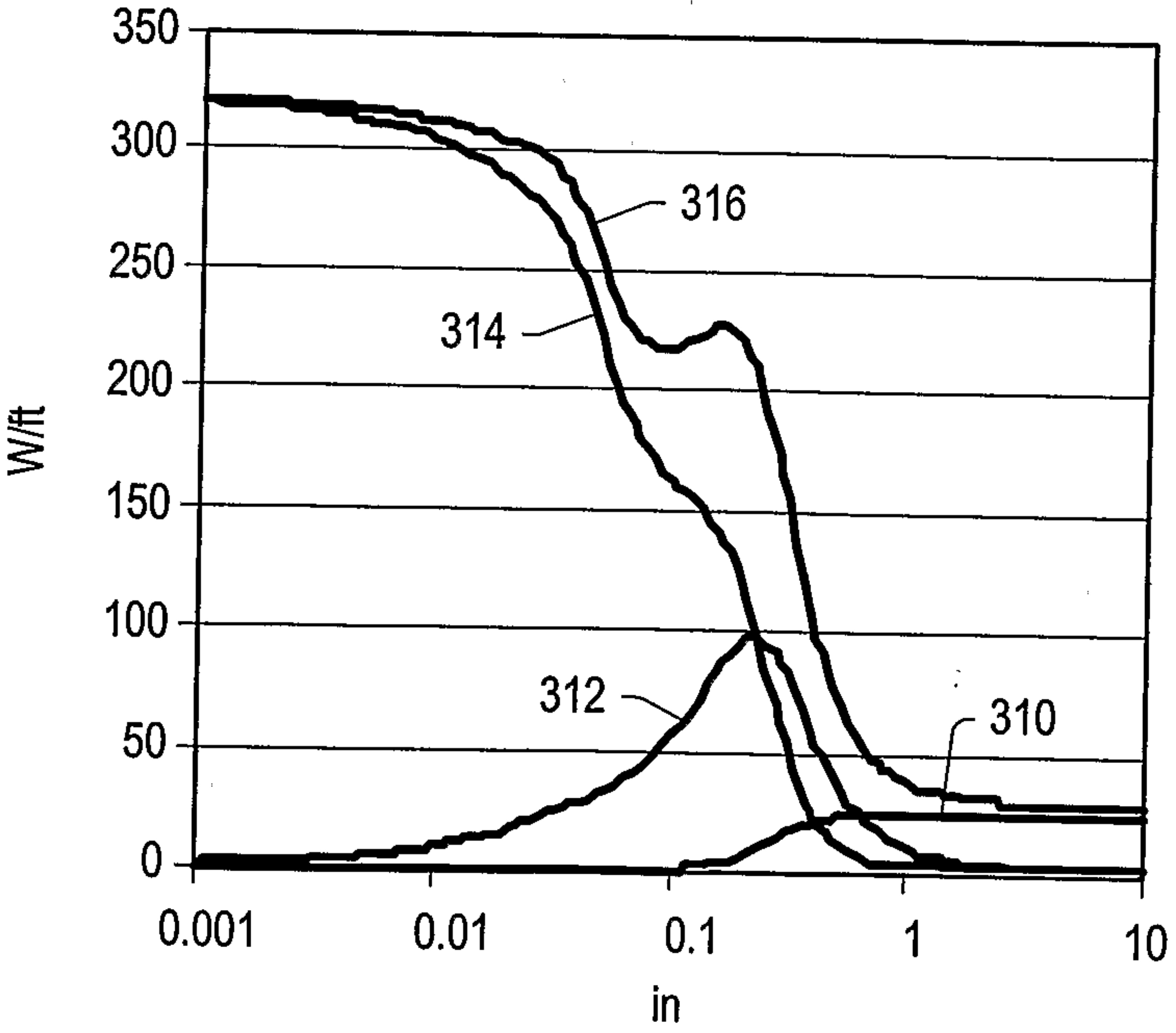
0.4
0.2
0
mΩ
0.001
0.01
0.1
1
10
in

FIG. 17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300
250
200
150
100
50
0
W/ft
316
314
312
310
0.001
0.01
0.1
1
10
in

FIG. 18

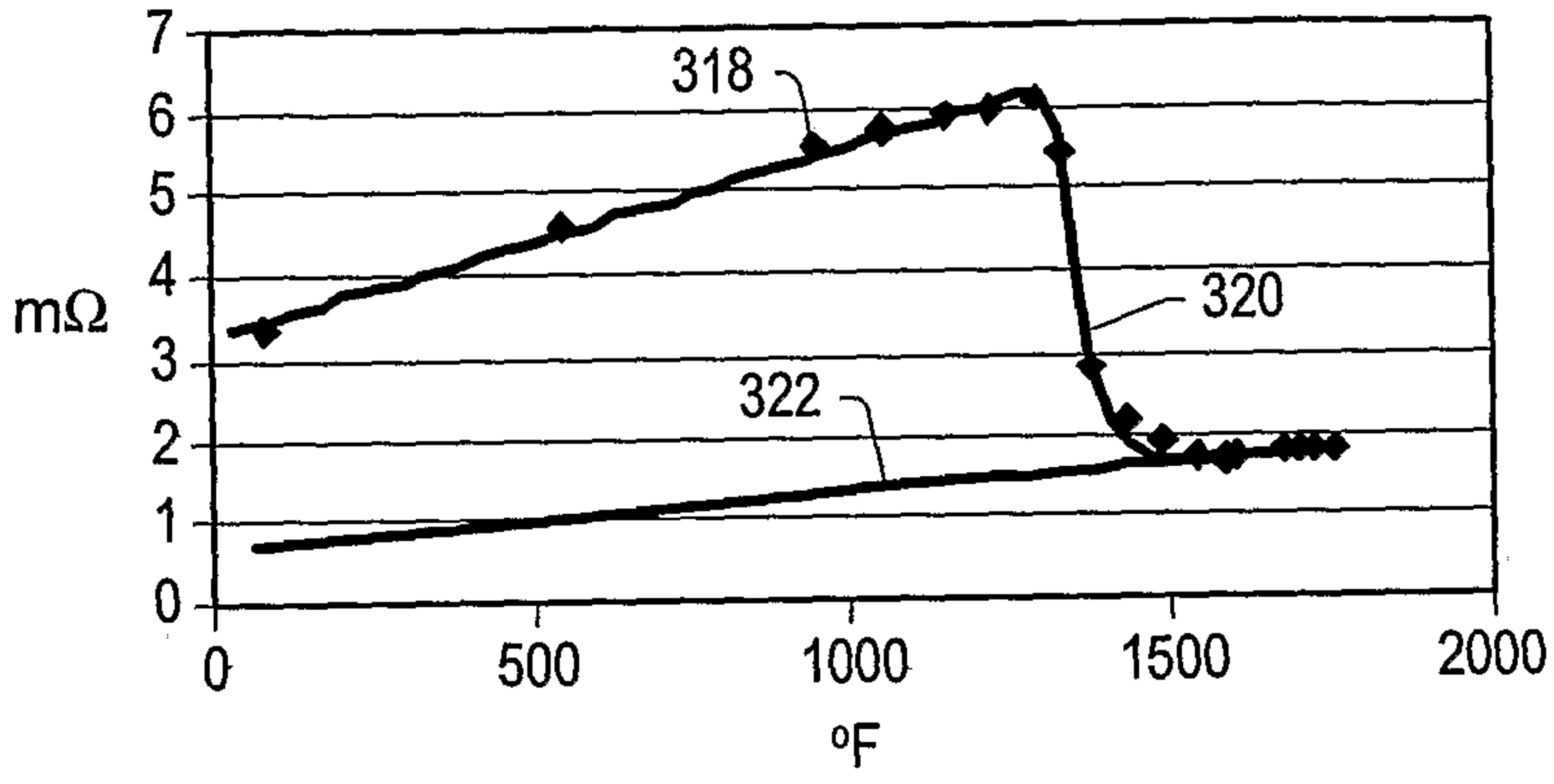


FIG. 19A

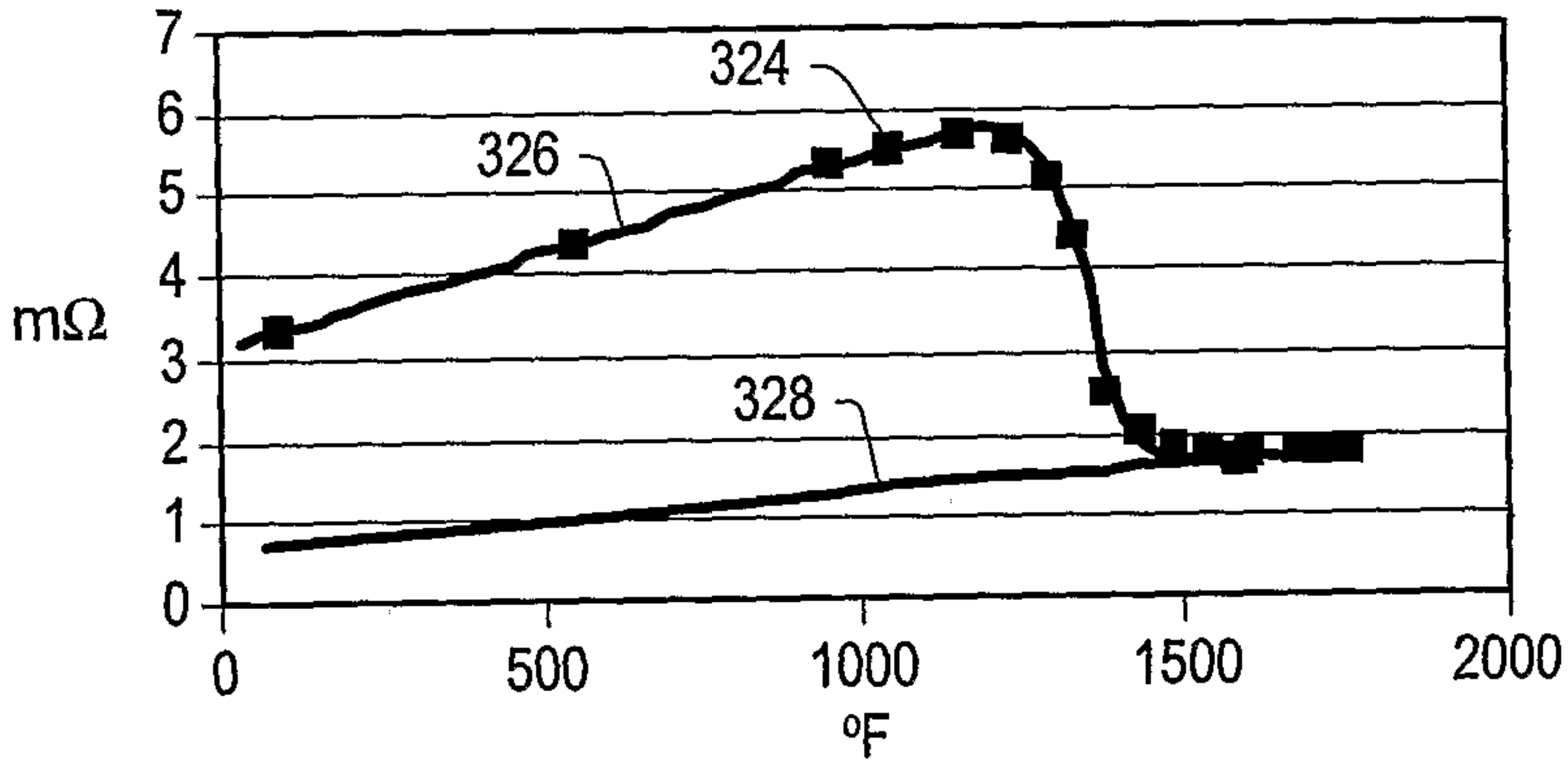


FIG. 19B

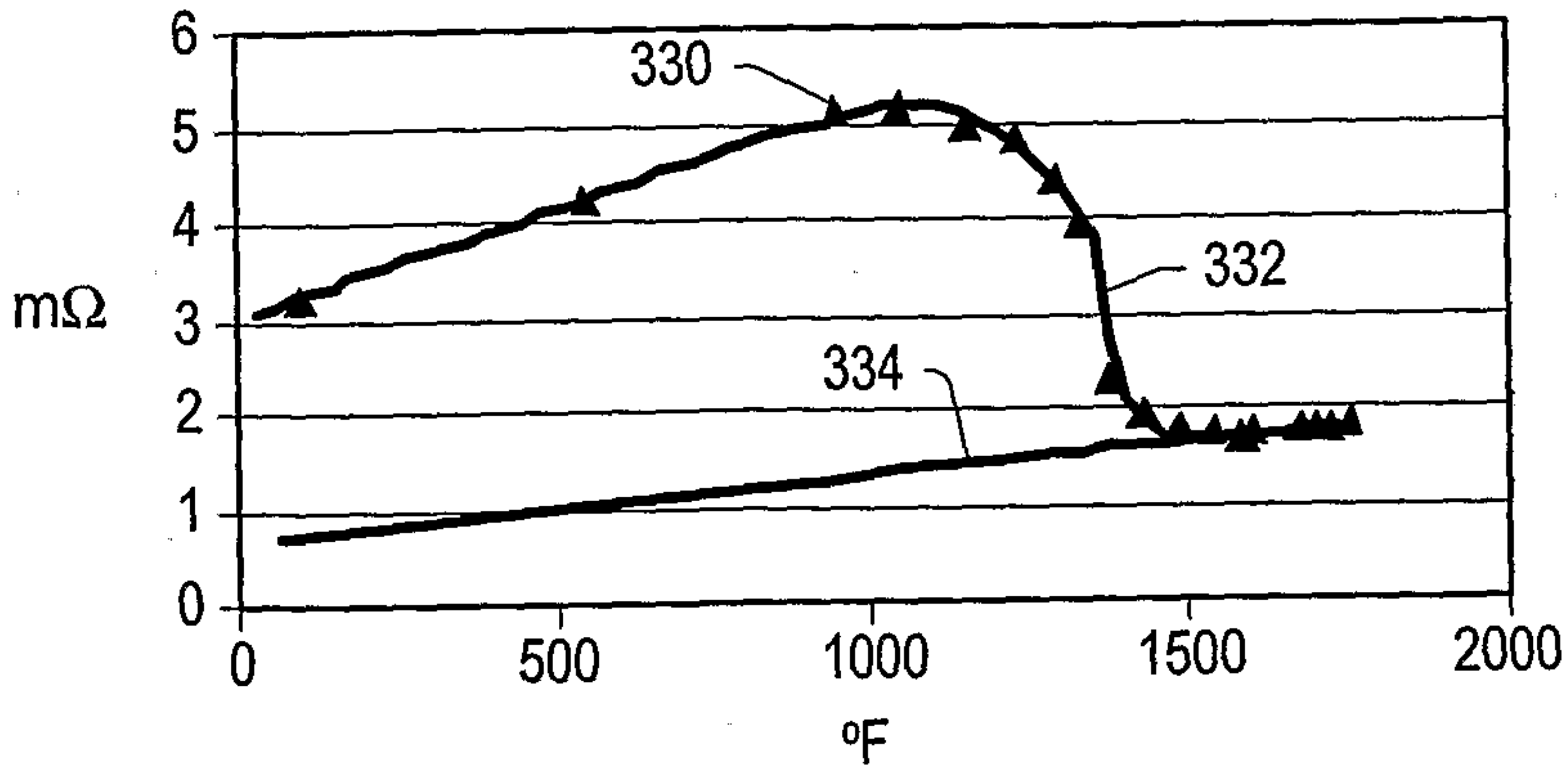
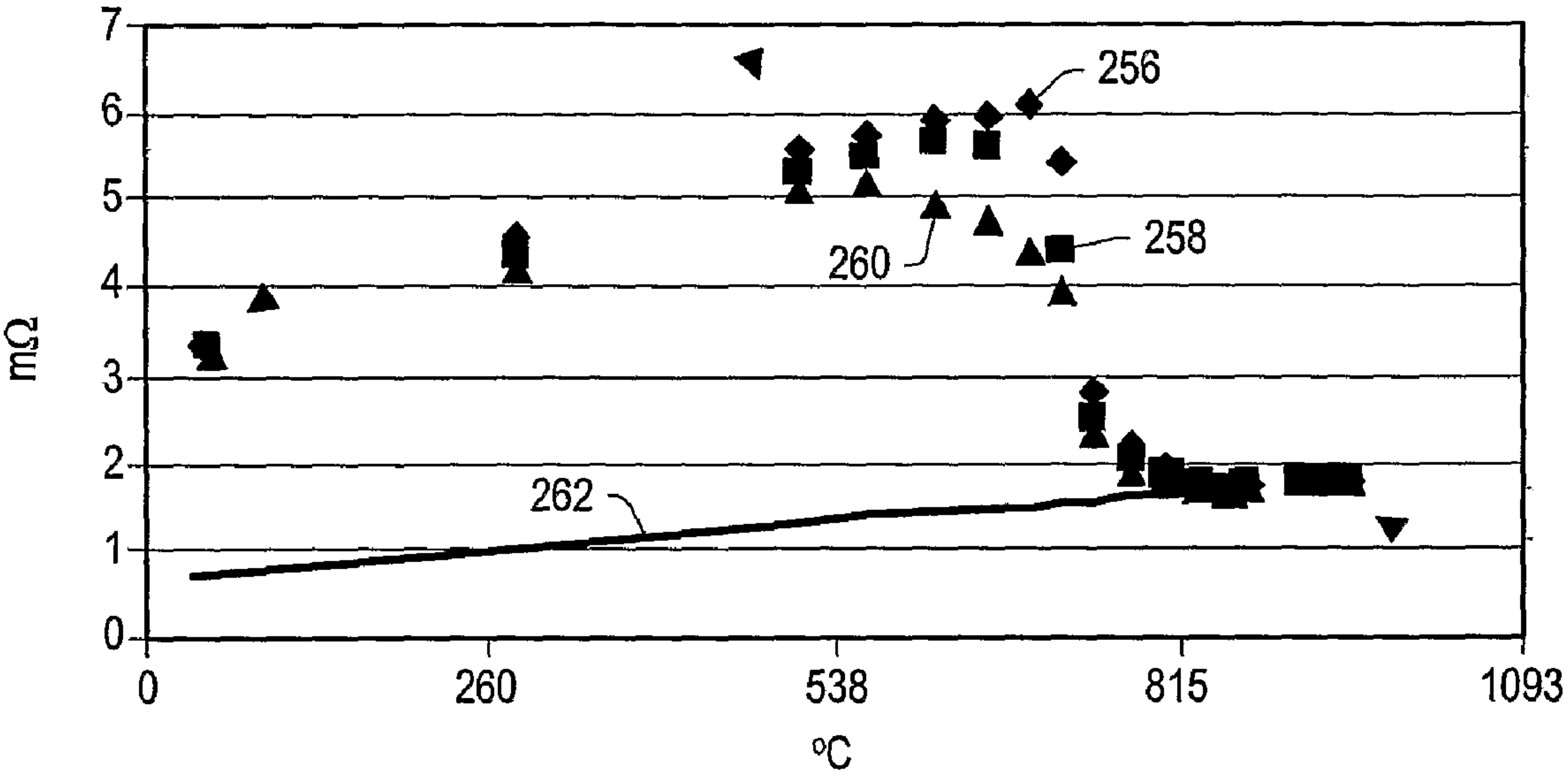


FIG. 19C



7
6
5
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3
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mΩ
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260
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1093
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